CFD MODELING OF FOREST CANOPY FLOWS: INPUT PARAMETERS, CALIBRATION AND VALIDATION

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Abstract

Wind flow simulations on forested zone have been performed with Computational Fluid Dynamics (CFD) software Meteodyn WT, which allows introducing a custom forest canopy model. The influence of parameter changes on results is investigated. The calibration of model parameters is done by minimizing the error between the CFD results and the vertical wind profiles given by the European standard Eurocode 1 (EC1), applied to standard terrains for high roughness cases. The calibrated model shows good coherence with EC1. To check the validity of the forest modeling in the real case, CFD simulation has been performed on a site with heterogeneous forest covering. The computed wind characteristics are then compared to met mast measurement. The comparison shows good agreement on wind shear and turbulence intensity between the simulation results and the measured data.

Keywords: wind flow simulation; forest canopy model; CFD; parameter calibration; EC1; wind engineering

1. Introduction

In atmospheric boundary layer, perturbations induced by ground surfaces with high roughness values, such as forests, generate a high level of turbulence and strong wind shear, which have clearly an influence on the calculation of wind load on structures [1], the site verification for wind farms, and even the assessment of annual energy production of wind turbines [2]. Thus the effect of forest must be taken into account in wind engineering and wind energy assessment to better estimate the mean wind profile and turbulence intensity.

In the study, wind flow simulations have been performed with CFD software Meteodyn WT, which allows introducing a custom forest canopy model.

The main objectives of the study are:

- Investigating the influence of changes of model parameters on the results
- Calibrating the CFD model according to the mean wind speed and turbulence intensity given by the European standard EC1, applied on flat homogenous terrains
- Checking the accuracy of the CFD modeling by comparison with measurements on a real site with heterogeneous forest covering

2. Numerical method

The CFD code Meteodyn WT solves the full Reynolds-Averaged Navier-Stokes equations with a turbulence closure scheme obtained by the prognostic equation on the turbulent kinetic energy (TKE) *k*, and a mixing length approach for the dissipation term (k-L model, developed by Yamada and Arritt [3], dedicated to atmospheric boundary layer applications). Even though it includes different atmospheric stability conditions for the simulation, the stability is set to be neutral in this study. Then the isothermal equations are solved and the turbulent viscosity formulations are considered for the neutral case.

The perturbations induced by forests are modeled by including sink terms in the momentum conservation equations for the cells lying inside the forested volumes:

$$f_V = -C_D \left|\overline{u_1}\right| \overline{u_1} \tag{1}$$

where C_D is a volume drag coefficient proportional to the forest density and depending on vertical leaf area profile.

Inside the canopy, both the production term and dissipation term are enhanced, thus additional terms are added into the TKE equation in which production and dissipation terms become:

$$P_k = \nu_T \left(\frac{\partial \overline{u_l}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i} \right) \frac{\partial \overline{u_i}}{\partial x_j} + \beta_p C_D \left|\overline{u}\right|^3 \tag{2}$$

$$\varepsilon = \frac{0.015 k^{3/2}}{L_T} + \beta_D C_D \left|\overline{u}\right| k \tag{3}$$

where v_T is the eddy viscosity, and L_T is the turbulence length scale given by $L_T=0.55l$, l being the mixing length. Following Liu (1996) [4], we consider $\beta_p = 1.0$ and $\beta_d = 4.0$.

The forest canopy height h_c, and the depth of the roughness sublayer h_{RSL} which is the region where the canopy directly impinges on the flow [5], can be expressed in function of the roughness length z_0, the parameters k_c and h_{add} [6]:

$$h_{RSL} = h_c + h_{add} \tag{4}$$

$$h_c = k_c z_0 \tag{5}$$

where h_{add} is the height of the additional dissipation's zone.
Furthermore, modifications of the mixing length are made in presence of forest canopy:

$$\begin{array}{ll} z<h_c & l^{-1} = l_0^{-1} + l_f^{-1} \\ h_c<z<h_{RSL} & l^{-1} = (1-\alpha)(l_0^{-1} + l_f^{-1}) + \alpha(l_0^{-1} + 1/kz) \\ z>h_{RSL} & l^{-1} = l_0^{-1} + 1/kz \end{array} \tag{6}$$

with $\alpha = (z-h_c)/(h_{RSL}-h_c)$, $l_f = 2$ m and $l_0 = 100$ m so that l approaches a constant value at higher level.

3. Influence of model parameters

The influence of the model parameters k_c (tree height/roughness ratio), C_D (drag coefficient) and h_{add} (height of additional dissipation's zone) is investigated in this section. The simulations are performed on flat homogenous terrains. The computation domain length is 6000 m. The horizontal resolution of the cells is set up at 25 m, and the vertical resolution is 4 m. The wind characteristics obtained at the centre of the computation domain, at different heights, are shown in Figure 1 to Figure 3. The roughness length used is 1.0 m in the presented case.

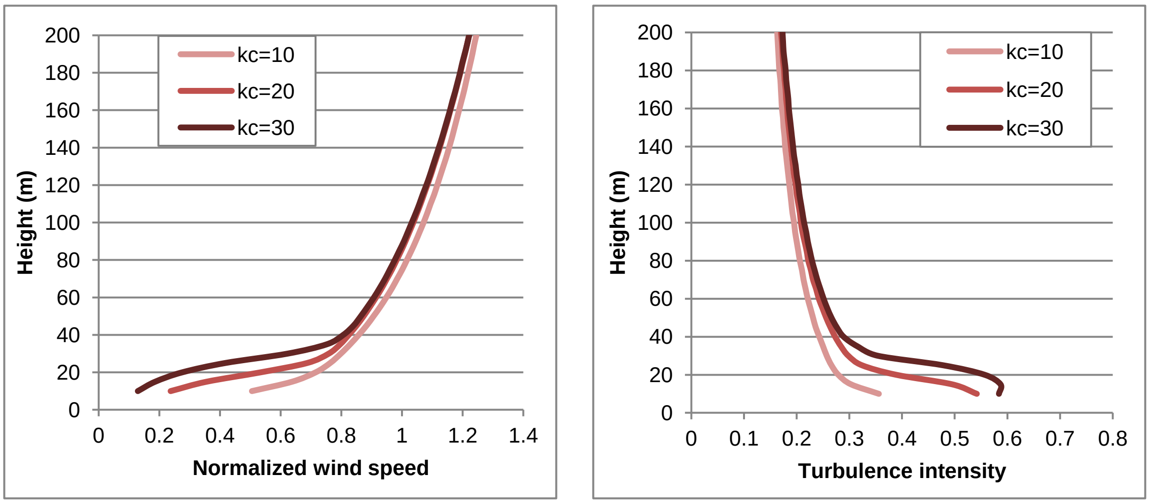

Figure 1. Computed mean wind speed and turbulence intensity profile for different values of k_c. The roughness length is fixed at 1.0 m, so that changing k_c is equivalent to changing the canopy height which is equal to 10 m for $k_c = 10$ and is equal to 30 m for $k_c = 30$.

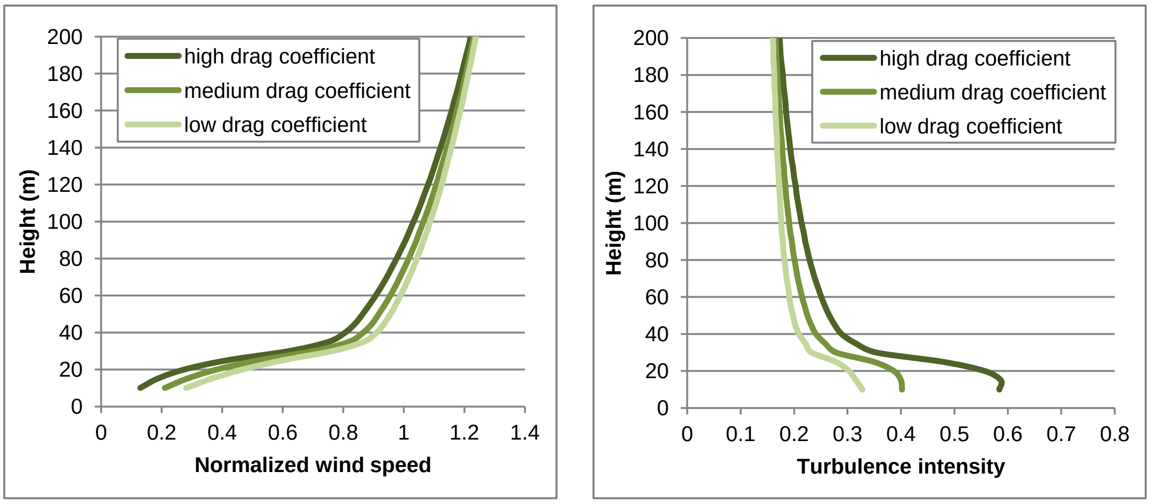

Figure 2. Computed mean wind speed and turbulence intensity profile for different levels of drag coefficient. The roughness length is 1.0 m and k_c is fixed at 30, so that the canopy height is equal to 30 m.

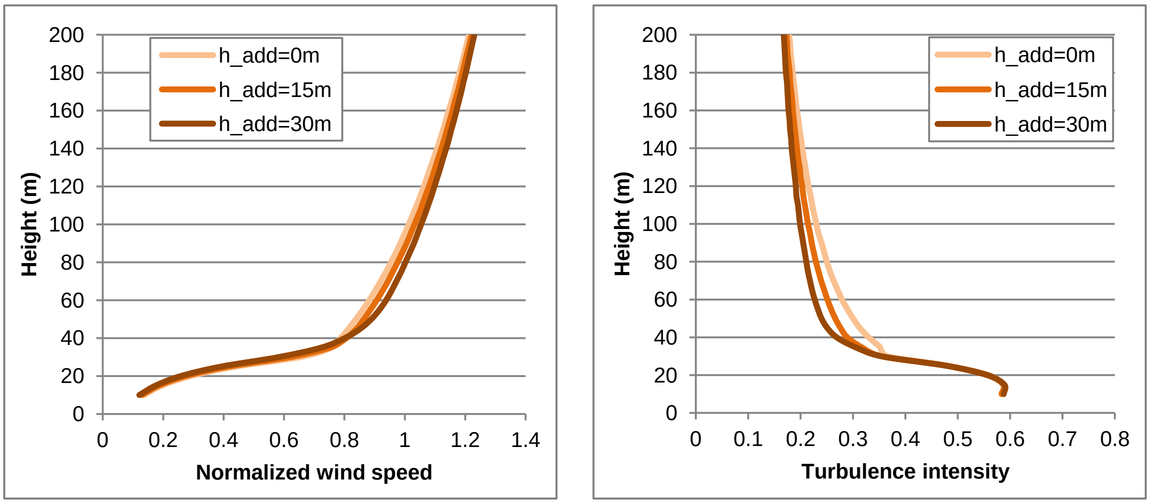

Figure 3. Computed mean wind speed and turbulence intensity profile for different values of h_{add}. The roughness length is 1.0 m and k_c is fixed at 30, so that the canopy height is equal to 30 m.

Inside the canopy, the velocity decreases while the turbulence is enhanced. It is no surprise that the change of k_c (so canopy height) has an obvious influence on the vertical profile of mean wind speed and turbulence intensity (Figure 1). The height of additional dissipation's zone affects principally the simulation results above the canopy height (Figure 3), while the drag coefficient affects both the results inside and above the canopy (Figure 2).

4. Forest Model Calibration

The default values of model parameters used in the software are k_c = 30, h_{add} = 15 m and C_D = 0.005. The calibration of these parameters has been done by comparing the CFD results to the vertical profiles given by Eurocode 1 (EC1), part 1-4: Wind Actions (EN 1991-1-4:2005E).

In case of standard homogeneous and flat terrains, EC1 gives formula to estimate the mean wind speed and turbulence intensity at different heights from the ground [7].

$$\frac{v_m(z)}{v_b} = \begin{cases} 0.19\cdot\left(\frac{z_0}{0.05}\right)^{0.07}\cdot\ln\left(\frac{z}{z_0}\right), z_{min} \le z \le z_{max} \\ \frac{v_m(z_{min})}{v_b}, z < z_{min} \end{cases} \tag{7}$$

$$I_v(z) = \begin{cases} \frac{1-2\cdot 10^{-4}(\log_{10}(z_0)+3)^6}{\ln\frac{z}{z_0}}, z_{min} \le z \le z_{max} \\ I_v(z_{min}), z < z_{min} \end{cases} \tag{8}$$

where z_0 is the roughness length of the ground, v_b is the reference wind which is defined as the wind speed at 10 m height above the ground with roughness length equal to 0.05 m, z_{max} is equal to 200 m and z_{min} varies from 1 m to 9 m according to the roughness length. In the calibration, we are interested in the results from 10 m to 200 m height.

With Meteodyn WT, numerical tests have been carried out on standard terrains with high roughness lengths: 0.2 m, 0.4 m, 0.6 m, 0.8 m and 1.0m. For each roughness length, the simulation was performed with different settings of the following parameters: k_c, h_{add} and C_D. The computation domain length is 6000 m. The horizontal resolution of the cells is set up at 25 m, and the vertical resolution is 4 m. The inlet wind and turbulence profiles are EC1 profiles.

The computed wind speed and turbulence intensity profiles in the case z_0 = 0.6 m and 1.0 m are shown in Figure 4 and Figure 5, from 10 m to 200m above ground, and compared with EC1 profiles. The wind speed is normalized with the reference wind.

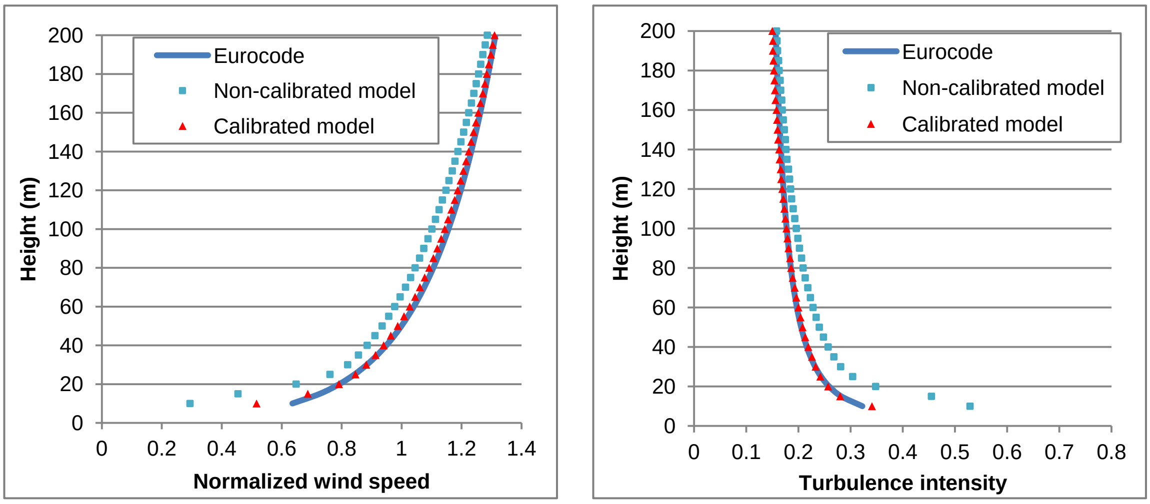

Figure 4. Computed wind speed and turbulence intensity compared to EC1 profiles for z_0 = 0.6 m

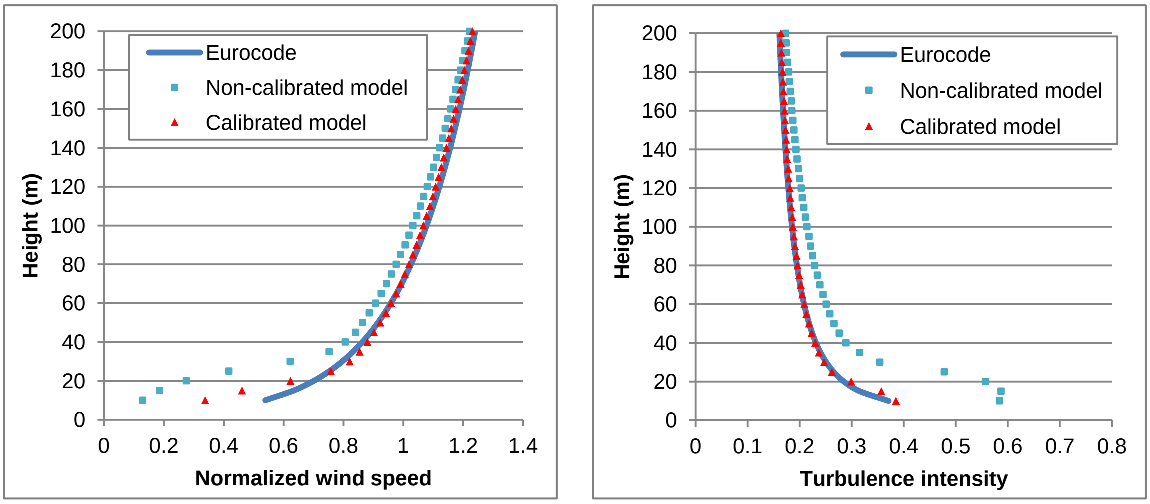

Figure 5. Computed wind speed and turbulence intensity compared to EC1 profiles for z_0 = 1.0 m

The numerical tests have led to values of k_c = 20, h_{add} = 15 m, and C_D = 0.002. The RMSE errors, taking into account all tested cases, are 0.024 for normalized velocity, and 0.009 for turbulence intensity. According to this result, the current default value of the parameters k_c has been changed to the calibrated value 20 in Meteodyn WT, which means that the ratio between the tree height and the roughness value should be 20 to better reproduce the EC1 profile on standard terrains. However, the value of the parameter C_D depends on the forest density on the specific site. The calibration carried out in this study gives a value in coherence with EC1, but one can always change its value according to the situation of the site studied.

The forest canopy model implemented in Meteodyn WT has been calibrated in order to get the mean wind speed and turbulence profiles as defined in EC1 for standard terrains. In this way, WT computations satisfy the continuity between the EC1 values for homogeneous terrains and more complex cases involving inhomogeneous roughness or orographic effects. That is also the condition for CFD methods to be commonly used and agreed by Building Control Officers in the calculation of wind load on structures [1].

5. Validation case

In order to check the accuracy of the calibrated forest model on complex terrains, a validation case has been carried out. The site is located in the east of France. The maximum difference in elevation inside the simulation area is about 160m. The orography around the met mast is visualized in Figure 6. The site is covered by heterogeneous forest. The canopy heights vary from 4m to 30m. A high resolution roughness data (horizontal grid step = 5 m) provides the information on canopy heights. The corresponding roughness map is shown in Figure 6.

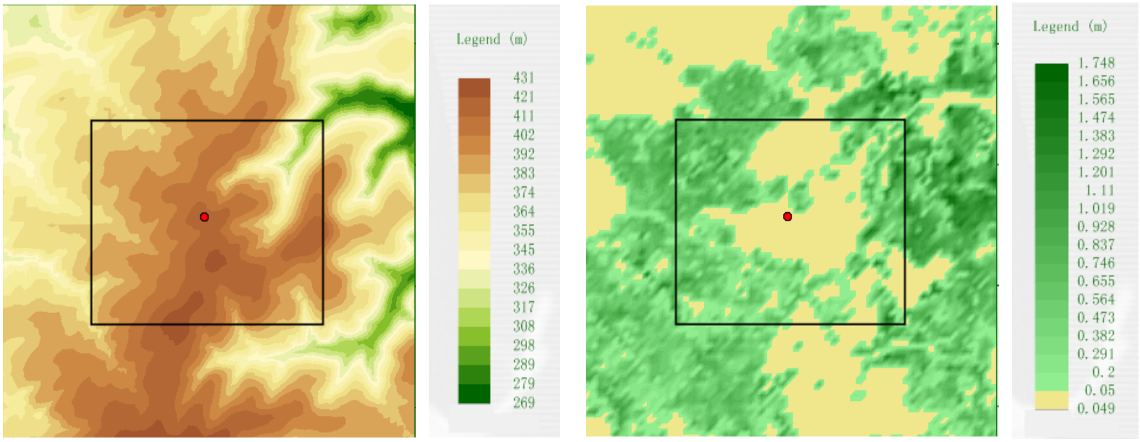

Figure 6. Elevation (left) and roughness (right) map of the site. The mapping area (20 km^2) is marked with a black rectangle.

The closest distance between the met mast and the forested zones is approximately 200 meters (in the north-east direction). The computation domain is 110 km^2 and is centered on the met mast location. A mapping area of 20 km^2 is defined, where the minimal horizontal mesh resolution 25 m is applied. Outside of this zone, the size of the cell increases, following a geometrical expansion coefficient which is set to 1.1. The minimal vertical resolution is set to 4 m. It is applied to cells from the ground up to 40 m height. Above, vertical dimensions of the cells increase, following a geometrical coefficient which is set to 1.2.

The met mast is equipped with anemometers located at three different heights (10 m, 30 m and 50 m). Two wind vanes are installed (30 m and 50 m). The highest wind vane is not used, due to the poor number of valid measurements collected on it. The measurement period is equal to 3.2 years from June 2005 to September 2008. Some of the collected data were corrupted due to icing effects.

The detection of anomalies is made by considering:

- Standard deviation of wind direction must be greater than 1 degree;
- Standard deviation of wind direction must be inferior to 50 deg;
- Standard deviation of wind speed must be greater than 0.1 m/s (except when mean wind speed be inferior 1 m/s);
- Discrepancies between anemometers at the same mast;
- The turbulence intensity must be inferior to 0.5.

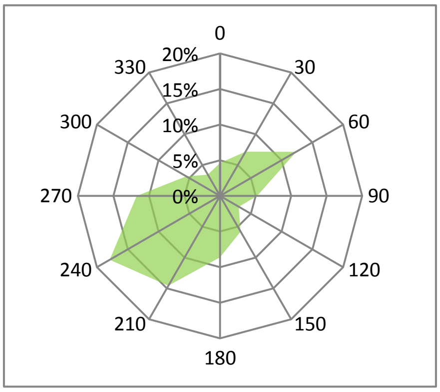

Figure 7. Wind frequency rose at 30 m height

The total number of valid records equals to 157 357, with a recovery rate of 93.24%. The wind frequency rose at 30 m is shown on Figure 7.

Furthermore, we assume that the thermal stratification is neutral in the simulation. Then it is necessary to remove the thermal effect by applying a strong wind filter on the measurement: only the records with wind speed greater than 10 m/s at the height of 30 m are considered, leading to a total number of strong wind records equal to 5 567.

CFD simulations allow getting the wind profile as well as the turbulence intensity at different heights of the met mast, for different directions. The simulation results are than compared to the measurement (strong wind data). Figure 8 shows the computed and measured mean wind speed taking into account all directions, and Figure 9 shows the computed and measured directional wind profiles (normalized by the wind speed at 30 m height) for the directions with enough strong wind records. Compared to the measured data, the error on mean wind speed, taking into account all directions, extrapolated from 30 m height, is 1.5% at 50 m and -4.7% at 10 m (Table 1). The error on directional vertical extrapolation of wind speed is given in Table 2. Figure 10 shows the directional turbulence intensity. The error on directional turbulence intensity is given in Table 3.

Table 1. Mean wind speed extrapolated from 30 m height, compared with measured data

Height (m)	Computed wind speed (m/s)	Measured wind speed (m/s)	Relative error
10	9.9	10.3	-4.7%
50	12.5	12.3	1.5%

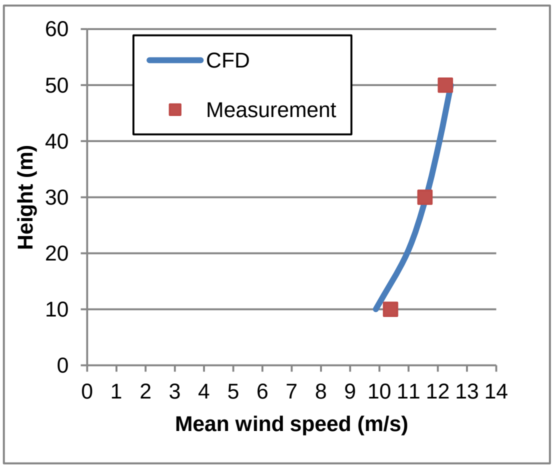

Figure 8. Measured and computed mean wind speed. The computed wind speed is extrapolated from the measurement at 30 m height.

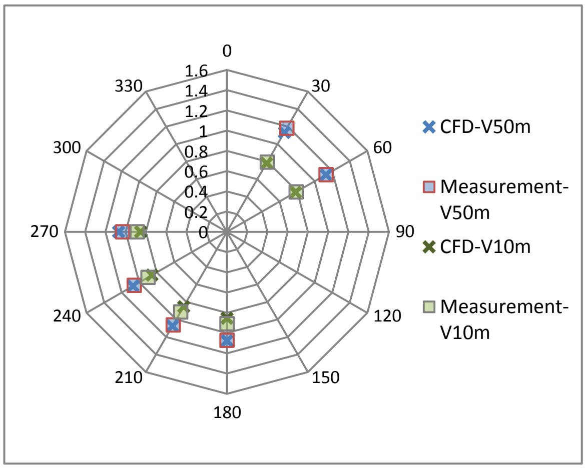

Figure 9. Measured and computed directional wind speed, normalized by the wind speed at 30 m height.

Table 2. Error on the vertical extrapolation of wind speed for different direction sectors. The wind speed has been normalized at 30 m height. The relative error is less than 5% for most directions.

Direction sector	30	60	180	210	240	270
Relative error 50 m	-4.0%	-0.1%	0.3%	1.2%	1.3%	3.8%
Relative error 10 m	-1.7%	-1.1%	-5.9%	-6.5%	-5.0%	-3.8%

Table 3. Error on the turbulence intensity estimation at 50 m height. The error is less than 0.005 for most directions.

Direction sector	Measured TI	Computed TI	Error
30	0.161	0.161	0.001
60	0.149	0.15	0.001
180	0.154	0.156	0.002
210	0.158	0.162	0.004
240	0.146	0.154	0.008
270	0.154	0.148	-0.006

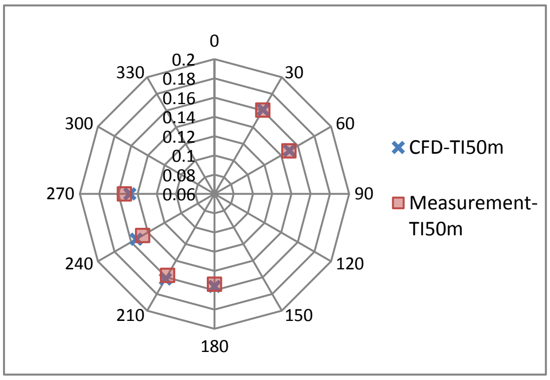

Figure 10. Measured and computed directional turbulence intensity at 50 m height

The measured wind shear and turbulence intensity are not homogenous in different directions. That is probably caused by the heterogeneity of orography and forest covering. In this study, the wind characteristics are especially affected by the distance between the met mast and to nearest upstream forest, which varies with the direction.

In the CFD simulation, the orography and roughness effects are coupled as they are in the real world. The simulation is able to reproduce the measured wind shear and turbulence for different wind directions. The results show good match with the measurement for both mean and directional values.

6. Conclusions

The forest canopy model implemented in the CDF software Meteodyn WT has been calibrated. Based on numerical tests, a new parameter setting for the forest model is retained. Particularly, the tree height/roughness ratio should be 20. The calibrated model shows good coherence with the standard EC1 for both wind speed and turbulence intensity in standard terrains.

The wind flow over a real site with heterogeneous forest covering has been simulated. The wind characteristics at the met mast are obtained by taking into account the heterogeneity of the orography and the forest as well as the coupling between orography and forest. The simulation results are than compared to the met mast measurement, both the mean and directional values being checked. The comparisons show that the CFD modeling, with the appropriate forest model, is able to reproduce the wind speed profile and turbulence intensity in complex terrains with an acceptable accuracy.

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