Modelling of atmospheric boundary-layer flow in complex terrain with different forest parameterizations

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Abstract. This work explores the accuracy of two approaches that account for the effects of the forest canopy on the wind flow by using a RANS-based model. The first approach implements additional terms in the RANS equations (canopy model), whilst the second one uses large values of roughness length and a zero-plane displacement height. The model uses a limited-length-scale k-ε turbulence closure that considers processes occurring in the Atmospheric Boundary-Layer (ABL) such as the Coriolis effects. Both the forest and the ABL implementations are compared with experimental data obtained from 118 m high met masts installed in a large mountain-range site with mixed forest characteristics for neutral stability cases. In order to perform a meaningful comparison at multiple mast locations, a novel methodology is presented which allows the selection of a velocity bin for a given wind direction and a stability class that minimizes the error of using short-term measurement periods at some masts compared to long-term wind statistics from a reference mast. Based on the outcome of the model validation it is possible to conclude that more consistent results are obtained by the canopy model since it reduces the uncertainty in the selection of correct input parameters in the large-roughness approach. The errors in the vertical profiles of velocity and turbulence intensity are reduced by the forest model by almost 63% and 11%, respectively, compared to the standard configuration (no forest). The large-roughness method reduces the error in the velocity profiles by 54% while the predictions of turbulence intensity are barely improved.

Abbreviations and acronyms: Ax, Turbine Position (x=1-6); ABL, Atmospheric Boundary Layer; CFD, Computational Fluid Dynamics; CENER National Renewable Energy Centre (Spain); KS, Kolmogorov-Smirnov; MOST, Monin-Obukhov Similarity Theory; MPx, Reference met mast (x=0,1,3,5,6); RANS, Reynolds-averaged Navier-Stokes equations; SBL, Atmospheric Surface-Layer; SIMPLE, Semi-Implicit Method for Pressure Linked Equations; CFDWind, CENERs CFD model for atmospheric flow

1. Introduction
Traditionally, the use of models based on the Reynolds-averaged Navier-Stokes equations (RANS) for wind resource assessment applications has relied on the Monin-Obukhov Similarity Theory (MOST). While this approach provides a good depiction of Surface Boundary Layer (SBL) flows in complex terrain sites, it only accounts for approximately 10% of the whole Atmospheric Boundary Layer (ABL) where the Coriolis effects are usually neglected and the mixing length is scaled linearly with height. Since the increasing size of modern wind turbines can in some cases reach heights at which MOST assumptions are not necessarily valid, ABL
considerations might help to reduce the uncertainties in the wind predictions beyond the surface-layer. Different works have addressed the extension of the SBL to include some of the ABL physical processes in two equation closure models (e.g. [1–5]). However, excepting few studies, the validations are mostly focused on flat, offshore or smooth-terrain cases.

Apart from the boundary-layer considerations, the additional capability of these models (both, SBL and ABL) to include the effects of vegetation elements is required by much of the wind resource assessment community [6]. This ability has been broadly investigated in the past decades through a wide variety of methods and for many applications [7, 8]. While acceptable results have been found for some of these methods in complex terrain studies [9], there is still a lack of agreement on which approach is best.

Considering the above, two main goals are pursued in this work: 1) compare the effects of the use of the ABL against the SBL modelling approach for the simulation of the wind flow in a mountain-range site, and 2) explore the accuracy between two methods to account the effects of the forestry in the wind fields: Including explicit source/sink terms to parameterize the canopy in the RANS equations (e.g. ([9–13])) versus the more practical solution of using large values of aerodynamic roughness length $z_0$ and a vertical translation $d$ of the bottom boundary in a post-processing step [14, 15]. For this purpose, the atmospheric model that considers the plant drag embedded into an ABL formulation recently developed by Sogachev et al. [5, 16] over flat terrain is implemented in the CENER’s Computational Fluid Dynamics (CFD) wind flow model and validated in the Alaiz experimental test site for neutrally-stratified situations.

The validation consists of a comparison between simulated and measured vertical profiles of wind velocity and turbulence intensity at three (out of the eleven positions of the site calibration campaign) 118 m high Alaiz met masts, two of which are located within a dense forest area. This site is characterized by highly directional winds, with northern being the most energetic, consequently, only this sector is considered. Since the three masts have different data availability, in order to obtain meaningful validation data sets, it is necessary to carefully pre-process the measured data. This step is carried out by a methodology (detailed in section 2.2) that optimally selects the velocity bin for a given wind direction sector and stability class based on the best representativeness of the short-term data compared to the long-term measurement period from the reference mast.

2. The Alaiz case study

The Alaiz test site is located on top of the Alaiz-Las Balsas Mountain in the Navarra Province, Spain. To the North, a large valley is found at around 700 m lower altitude. To the South, complex terrain is found with the presence of some wind farms; the closest one situated 2 km behind the row of six wind turbine stands of the test site (see [17] for more details about terrain characteristics). Figure 1 presents the five reference met masts (MP0, MP1, MP3, MP5 and MP6), 118 m tall, which are located in front (North) of the turbine positions (denoted as A1-6) at a distance of around 250 m. The close-up image in this figure shows the layout of the park in which the three masts used in this study (MP5, MP1 and A1) are highlighted with a star symbol.

The vegetation in the site might be characterized by two main roughness levels. The north-eastern part (where the MP5 is located) is covered by low bushes not higher than 0.5 m where a $z_0 = 0.05m$ has been assumed. The western part, limiting with the MP3 position and delimited by green lines in Figure 1 is covered with a dense canopy composed of bushes and beech trees of 10-15 m high whose roughness is denoted as $z_0 = $forest and discussed further in section 3. The roughness values of Alaiz are determined by visual inspection and orthophotos from the Navarras land survey agency SITNA [18]. The roughness values of the surrounding region are extracted from the CORINE land cover data set [19]. The correspondence from land use to $z_0$ is taken by the guidelines provided by Wieringa et al. [20].
Figure 1. In the left panel an aerial image of the Alaiz region is shown together with the roughness length $z_0$ assigned to the surroundings of the mountain. The domain extension used for the CFD simulations (section 4) is also shown with dotted black line. To the right it is depicted a close-up of the test site and the surrounding vegetation.

The test site has been operational since end of 2009 with the first wind turbines installed in the summer of 2011. The standard configuration of each mast includes cup anemometers and wind vanes at 78, 90, 102, 118 m and temperature/humidity measurements at 81, 97, 113 m. Replicated cup anemometers are situated 2 m below the reference ones. The MP5 position, reference met mast of the site, is equipped with an extra cup anemometer at 40 m and two vertical propellers at 78 and 118 m. Two temperature/humidity sensors at 2, 38 m were installed in January 2011 to characterize the temperature stratification of the lower part of the boundary layer (see [17, 21] for a detailed instrument’s set-up).

2.1. Site calibration measurement campaign

The site calibration campaign is of special interest for the validation of microscale flow models since it provides local speed-up factors between the reference mast and the turbine positions. The site calibration in Alaiz consists of two phases corresponding to the eastern site calibration (A4-A5-A6 vs MP0-MP5-MP6) and the western site calibration (A1-A2-A3 vs MP1-MP3-MP5).

The duration of these short-term campaigns, around 5 months, are compliant with IEC 61400-12-1 to make sure that enough samples are obtained from the relevant testing north sector. The norm makes no distinction between different stability regimes for power performance testing. When the data is subdivided into stability classes the statistical significance of the measurement period may be compromised by the short duration of the campaign. Hence it is important to perform the following assessment of the long-term representativeness of the bin-averaged site calibration speed-up factors before using them for model validation.
2.2. Generation of quality-controlled validation data sets

Standard practice in the processing of validation data sets from field campaigns typically imply synchronizing the measurements from collocated met masts to derive mean profiles based on the same samples. While this approach produces statistics based on the same wind climate population, it requires that all the met masts operate at the same time for a long-enough period. An alternative approach is proposed here wherein validation data is produced by synchronizing each short-term met mast individually with a reference long-term met mast (MP5 in this case). Then, the long-term representativeness of each met-mast validation data set is assessed by comparing the statistics between the short-term and the long-term population at the reference met mast. This scenario is typical of conventional resource assessment campaigns, where a reference met mast is installed to monitor the wind conditions and, once the project is well advanced in the planning phase, additional met masts are installed to decrease uncertainties in areas of distinct terrain characteristics to the reference met mast.

The validation data set consist of bin-averaged profiles of velocity and turbulence intensity ($I_U = \sigma_U/U$, where $\sigma_U$ is the standard deviation measured by the cup anemometer), where each bin is defined by a velocity, wind direction and stability classes. The velocity profiles are made dimensionless by dividing by the top-level velocity at MP5 ($U_0$). The stability classification is based on the Froude number ($Fr$) through the methodology described by Sanz-Rodrigo et al. [21].

The long-term representativeness of each met mast data set is determined by comparing the short-term and long-term distributions of the reference mast considering the three flow-driver variables that are used to define the bin statistics: wind direction, wind speed and stability. The two-sample Kolmogorov-Smirnov non-parametric test is used to determine if the data of the short-term period comes from the same parent distribution of the long-term period. The result of the test is $KS = 0$ is both data sets share the same parent distribution and $KS = 1$ otherwise. The maximum absolute difference between the two cumulative probability distributions ($KS_{stat}$) is used to determine how much they differ. Finally, a metric $E_{rep}$, is used to determine how the profiles of mean velocity and turbulence intensity differ from the short to the long term period:

$$E_{rep} = \sum_{m=1}^{N} \left| \langle X_m \rangle_{long} - \langle X_m \rangle_{short} \right|$$

where $\langle X_m \rangle = \{ \langle U_m \rangle, \langle I_m \rangle \}$ is either the bin-average mean velocity or turbulence intensity at the sensor level $m$ for a reference met mast with $N$ levels and $\langle X \rangle_{long}$ is the mean value of the all the sensor levels of the long-term bin-averaged profile.

This methodology allows to select the best velocity bin for a given wind direction sector ($D$) and stability class. The optimization criteria consists on selecting the bin that is present in every met mast data set (i.e. the number of samples is more than 10 in all the met-masts) and has the largest number of samples (this typically leads to minimum errors).

Table 1 shows the results of the long-term representativeness analysis when this is applied, resulting in the selection of the 11 m/s velocity bin. The mean velocity profiles are statistically converged within a 3% mean absolute error while the mean turbulence intensity profiles are within 20%. These errors are likely the largest contributions to the measurement uncertainty. Since this statistic provides an objective measure of the uncertainty associated to the representativeness of the short-term measurement periods in MP1 and A1 masts, this metric is used to summarize the overall model’s performance by providing a weight in the average scores (see section 5).
Table 1. Long-term representativeness of the validation data of each mast for northern sector \((345^\circ < D \leq 15^\circ)\), neutral conditions \((-0.2 < Fr^{-1} \leq 0.2)\) and 11 m/s \((10 < U < 12 m/s)\).

| Mast | N  | \(E_U^{ref}\)[%] | \(E_I^{ref}\)[%] | \(KSD\)  | \(KS_{statD}\) | \(KS_U\)  | \(KS_{statU}\) | \(KS_{Fr}\) | \(KS_{statFr}\) |
|------|----|----------------|----------------|-------|-------------|-------|-------------|-------|-------------|
| A1   | 114| 2.5           | 19.5          | 1     | 17.7        | 0     | 10.4        | 1     | 19.6        |
| MP1  | 118| 2.8           | 18.3          | 1     | 18.2        | 0     | 12          | 1     | 20.3        |
| MP5  | 693| 0             | 0             | 0     | 0           | 0     | 0           | 0     | 0           |

3. Numerical model
CENERs wind flow model (so-called CFDWind) is used for all the simulations presented in this study. This RANS-based model is currently implemented in the finite-volume solver OpenFOAM v2.1[22] for incompressible flows under neutral stratification and steady-state conditions. Turbulence closure is achieved using eddy-viscosity theory and the standard \(k – \varepsilon\) closure scheme modified for atmospheric flows [3, 23]. SIMPLE algorithm is employed to solve the pressure-velocity coupling whilst 2nd-order upwind schemes are used for the discretization of both velocity and turbulence convective terms. This model has two versions: v1.0 that deals with SBL flows and v2.0 configured for ABL simulations as described below. Different validation exercises for both models can be found in [24].

3.1. Surface boundary-layer model
CFDWind v1.0 is based on MOST, which implicitly assumes that the mixing length \(l_m\), increases proportionally (linearly) to the wall distance[1]. The \(k – \varepsilon\) coefficients are calibrated for atmospheric flows complying with the consistency derived by Richards and Hoxey [23]. The inlet and top boundary conditions are also essentially those of Richards and Hoxey. This way it is obtained the well-known logarithmic velocity profile together with height-independent shear stress, turbulent kinetic energy \(k\), and wind direction (since Coriolis effects are neglected) when applied to horizontally-homogeneous and steady-state conditions [24].

Fixed values of velocity and turbulent quantities are imposed at the top of the domain in order to preserve a constant shear stress. The outlet boundary is defined as a pressure outlet while symmetry conditions are applied to the lateral sides.

At the ground, assuming wall bounded flow, a \(z_0\)-based wall treatment is implemented. The applied horizontal kinematic shear stress, dissipation rate and production term of the turbulent kinetic energy equation at the wall are computed with local values of velocity and turbulent kinetic energy of the cells next to the ground. However, it should be highlighted that, similar to Parente et al. [25] (which differs from [23, 26]), the production term is not integrated over the first cell height as, comparable to their findings, larger deviation from the theoretical MOST turbulent kinetic energy profile was observed in the second cell above surface.

Similar to Sørensen et al. [26], the wall functions consider that the first cell is placed at the height \(z_0\). In this manner the restriction related to the dependency of the vertical size of the first cells and the values of \(z_0\) is avoided.

3.2. Atmospheric boundary-layer model
CFDWind v 2.0 deals with ABL flows. It simulates the transition to geostrophic wind in the top boundary, where by definition friction is zero, by adding explicitly to the momentum equations the Coriolis apparent force (equation 2) together with the horizontal pressure gradient force
(equation 3) derived from the hydrostatic relation for stationary cases [27].

\[ F_i = -\epsilon_{ijk}\Omega_j U_k \]  
\[ \frac{1}{\rho_0} \left( \frac{\partial P}{\partial x_1}, \frac{\partial P}{\partial x_2} \right)^T = f_c(-G_2,G_1)^T \]  

(2)  
(3)

where \( \epsilon_{ijk} \) is the Levi-Civita operator. By using well-known simplifications related to the negligible vertical components of both velocity and Coriolis force [27], \( F_i \) can be computed by using \( \Omega_j \) along the \( x_i \) directions (\( x_1,2 \) and \( x_3 \) are the horizontal and vertical directions, respectively). \( G_1 \) and \( G_2 \) stands for the geostrophic wind components in \( x_1 \) and \( x_2 \) directions, respectively.

In order to limit the length-scale, the ABL model adopts the solution proposed by Apsley and Castro [2] by modifying the \( C_{\epsilon 1} \) coefficient in the \( \epsilon \) transport equation as defined by equation 4. This limiter turns the linear growth of the mixing length \( l_m \) in the surface layer towards an asymptotic value, reducing turbulence mixing in the upper part of the boundary layer. This method is also consistent with the surface-layer scaling since it is reduced to the standard \( k-\epsilon \) when \( l_m \ll l_{\text{max}} \) [2].

\[ C^*_{\epsilon 1} = C_{\epsilon 1} + (C_{\epsilon 2} - C_{\epsilon 1})(l_m/l_{\text{max}}) \]  

(4)

where \( l_{\text{max}} \) is the maximum \( l_m \) estimated according to Blackadar [28] as:

\[ l_{\text{max}} = 0.00027|G|/f_c \]  

(5)

where \( G \) is the magnitude of the geostrophic wind.

3.3. Canopy model.

As mentioned previously, the perturbations induced by forests are modelled by adding the following drag term \( S_i \) in the momentum equations:

\[ S_i = -c_d A(z)|U_i U| \]  

(6)

where, as seen in equations 6 and 8, forest canopies are defined in terms of a drag coefficient \( c_d \), leaf-area-density (LAD) profile \( A(z) \) [m²/m³], and average forest height \( h \) which is used as the upper limit whose cells below are affected by the additional source/sink terms. \(|U|\) is the time-averaged velocity modulus.

As extensively discussed by [13, 16], in order to parameterize in a consistent manner the effects of the forest in the \( k-\epsilon \) model for ABL flows, only the additional enhanced dissipation term \( S_d \) is added to dissipation rate equation as follows:

\[ \frac{\partial \epsilon}{\partial t} + U_j \frac{\partial \epsilon}{\partial x_j} - \frac{\partial}{\partial x_i} \left( \frac{\nu_t}{\sigma_\epsilon} \frac{\partial \epsilon}{\partial x_i} \right) = \frac{\epsilon}{k} \left( C^*_{\epsilon 1} P_k - C_{\epsilon 2} \epsilon \right) + \frac{\epsilon}{k} \left[ (C^*_{\epsilon 1} - C_{\epsilon 2}) (-S_d) \right] \]  

(7)

where \( \nu_t \) is the turbulent viscosity which has to be solved to close the equations. \( \sigma_\epsilon \) is the Schmidt number and \( C_{\epsilon 2} \) is a model constant (both defined in Table 2). \( P_k \) is the rate of shear production of \( k \), and the \( S_d \) is computed by the approximation developed by Sogachev [16] as:

\[ S_d = 12C_{\mu}^{1/2} c_d A(z)|U|k \]  

(8)
3.4. The large roughness length and zero-plane displacement approach.

Instead of parameterizing the forestry, the effects of the canopy in the boundary-layer flows above the forest can be also accounted by increasing the values of roughness length and by artificially shifting from the ground the results a given distance $d$ along the vertical from the ground in a post-processing step (zero-plane displacement method) [14, 15]. This is a rather common approach in many computational models applied by the wind engineering community and despite its limitations, different authors have found satisfactory results both applied to linear and CFD models (e.g. [14, 29]).

For the sake of simplicity, in this work this method is addressed by testing two $z_0$ values in order to analyse the sensitivity of the method to the selected value. Thus, the $z_0$ of the patches corresponding to forest areas are changed to either $z_0 = 0.4$ m or $z_0 = 1.0$ m. These values are taken from the guidelines of the linear model WAsP. In both cases, from the same WAsP guidelines, a fixed displacement height of $d = 0.67h$ is applied.

4. Model Setup

In the first stage, a set of simulations of the site were carried out with two main purposes: a) perform a mesh and domain size sensitive analysis, and b) determine the appropriate value for geostrophic wind so that the velocity obtained at the MP5 position at 118 m is approximately 9 m/s, since this value is suggested within the guidelines of the Wakebench project [21]. No-gradient boundary condition was specified in the lateral sides while the modified wall functions (section 3.1) are used at the ground with a constant roughness of $z_0 = 0.03$ m. The Alaiz site is situated at a latitude $\phi = 42.65^\circ$ hence, $f_c = 9.88410^{-5}$ 1/s . Furthermore, since the desired geostrophic wind is 9 m/s, the resulting driving pressure gradient is $8.910^{-04}$ m/s$^2$. The constants of the $k – \varepsilon$ model listed in Table 2 are employed in all the simulations. These values are selected from the analysis performed by Detering and Etling [1] which comply with the consistency in the surface-layer [23]. The discussion about the impact of values of $C_\mu$ which is not calibrated in this study can be consulted in [13].

The sensitivity analysis described above concluded with the following model configuration:

- For ABL simulations, the steepness of the hill situated 7 km to the north of Alaiz produces a recirculation area that moderately influences the wind fields at the test site. Thus, the CFD domain (shown in Figure 1) covers an area of 6 km x 10 km such that this hill is included into the domain.
- A structured mesh of 25 m horizontal cell’s size is chosen out of three sizes tested (15, 25 and 40 m). Beyond the 6x10 km area, it is defined a transition zone of 5 km in every direction in which the cell’s size is continually increased up to a value 300 m. After this area, through a distance of 10 km the topography is massaged for 4 km until a flat terrain, artificially created, is reached.
- In ABL simulations, the top boundary should be placed sufficiently high to avoid not only possible interactions with the terrain, but also to allow the development of the entire ABL structure to a constant velocity value (geostrophic wind), consequently a domain height of 12 km is set.
- 50 layers are used for the vertical discretization, resulting in a final mesh of 9.8M cells.
- Since the CFD domain is characterized by a wide variety of roughness levels (see Figure 1), ranging from 0.03 m to 1 m (when the large-roughness method is applied), the first computational cell centre is placed at $z_1 \simeq 0.5$ m.
- The velocity profile obtained from the precursor simulation (which is used and inflow condition) is rotated in such a way that the incoming wind direction at 118 m is equal to zero (to simulate the Northern direction).
Table 2. Constants employed by the $k-\varepsilon$ model.

| $\kappa$ | $C_\mu$ | $\sigma_k$ | $\sigma_\varepsilon$ | $C_{\varepsilon 1}$ | $C_{\varepsilon 2}$ |
|----------|---------|------------|----------------------|-------------------|-------------------|
| 0.4      | 0.0256  | 0.7407     | 1.2987               | 1.13              | 1.9               |

4.1. Configuration of the canopy model

The characterization of the canopy structure is a subject of study by itself. Recent works propose novel methods to obtain accurate forest characteristics from aerial scans based on light detections and ranging systems [30]. However, because of the lack of the required information to perform complex analysis of the canopy properties, an average constant tree height of $h = 15$ m has been established for the forest area in the test site. The LAD for the canopy structure can be determined in a number of ways. Although it is evident that the flow within the canopy is highly dependent on the LAD description, it is not clear its impact on the wind and turbulence quantities at relevant heights for the wind energy industry in complex terrain. Therefore, the model’s sensitivity to this input information is tested with the following LAD configurations whose distributions are shown in Figure 4a).

- First, as it has been pointed out by Lopes da Costa et al. [29], constant foliage could be more appropriate in case of dense canopies. Thus, all simulations are carried out with this input. It is assumed a constant $LAD = 0.4 m^2/m^3$ whose value is determined from the Leaf Area Index (LAI) published in the literature for beech trees [31]; that is $LAI = 6$.
- The second test is a variable LAD profile, $LAD(z)$, which is defined through the empirical parametric function proposed by Lalic and Mihailovic[32]. For this case, by visual inspection the maximum observed $LAD$ ($LAD_m$) is assumed to occur at a height $z_m$, 0.7 times the tree height, i.e. $z_m = 0.7h = 10.5$ m. Since both $LAI$ and $LAD_m$ are considered to be constant in Alaiz, the value of $LAD_m$ is computed from the integral of the function $LAD(z)$ divided by the $LAI$ [32]. The result is an approximate value of $LAD_m = 0.86 m^2/m^3$.

Because of the lack of more detailed information about the forestry structure and following the recommendation of [30, 33, 34] a fixed value of 0.2 has been used for the drag coefficient $c_d$.

5. Results and discussion

In order to compare the model outputs with the validation data set, the simulated velocity magnitude $U$ and turbulent intensity $I$ are converted to dimensionless variables by using reference $U_0$ and $I_0$ values from the model’s results at the MP5 position at 118 m. As in section 2.2, the dimensionless number of velocity is simply defined as $U/U_0$, whereas the dimensionless turbulent intensity is computed through equation 9.

$$I/I_0 = \frac{(k/k_0)^{1/2}}{U/U_0}$$  \hspace{1cm} (9)

The comparison of vertical profiles of $U/U_0$ and $I/I_0$ obtained at the MP5 mast is presented in Figure 2. As mentioned earlier, the MP5 is located outside the forest patch and without the presence of forest in the upstream direction. Thus, as expected, there are no appreciable differences neither in velocity nor turbulence intensity between the roughness and the canopy model (grey and red lines). The slight differences between the two results are probably due to higher under-relaxation (and larger amount of iterations) specified to the forest model simulations in order to maintain numerical stability. On the other hand, this figure presents the differences between the surface and the atmospheric boundary-layer model described in section
3. It can be seen that while the SBL follows the logarithmic growth from 1 km up to the top boundary, the ABL presents the characteristic jet at $\sim 500$ m before decreasing to a constant value at the top (geostrophic wind). This ABL jet produces a higher shear in the first 100 m that is in better agreement with the measurements. Similarly it is observed the significant effects of the mixing-length limitation that produces a lower boundary-layer height deriving in larger values of turbulence intensity in the surface-layer.

![Figure 2](attachment:image.png)

**Figure 2.** Vertical profiles of non-dimensional velocity (left) and turbulence intensity (right) at the MP5 mast.

The concept of the normalized mean absolute error (equation 10) is employed for a second time as a proxy to measure the overall error $E_{X}^{\text{mod}}$, between observations $X_{m}^{\text{mast}}$, and model results $X_{m}^{\text{mod}}$. $X_{m}$ stands for either $(U/U_{0})_{m}$ or $(I/I_{0})_{m}$ at the $m$-th sensor level, and $X_{1}^{\text{mast}}$ is the mean value of the all the sensor levels at the given mast. These results are summarized in Table 3.

$$E_{X}^{\text{mod}} = \frac{\sum_{m=1}^{N} |X_{m}^{\text{mast}} - X_{m}^{\text{mod}}|}{X_{1}^{\text{mast}} N}$$  \hspace{1cm} (10)

As mentioned before, in order to summarize the overall performance of the forest modelling approaches, as denoted in equation 11, it is computed a weighted average $\langle E_{X} \rangle$ of the $E_{X}^{\text{mod}}$ statistic obtained at the two masts positions inside the canopy area (MP1 and A1). The weighting factor is determined as the complement of the normalized representativeness error $E_{X}^{\text{rep}}$ as stated in equation 12. In this manner more importance is given to the masts with smaller measurement uncertainty.

$$\langle E_{X} \rangle = \sum_{k} w_{k} (E_{X}^{\text{mod}})_{k}$$  \hspace{1cm} (11)

$$w_{k} = 1 - \frac{E_{X}^{\text{rep}}}{\sum_{k} (E_{X}^{\text{rep}})_{k}}$$  \hspace{1cm} (12)

where the subscript $k$ is $k = 1$ for the MP1, and $k = 2$ for the A1 error statistic used.

The results for the three canopy modelling approaches implemented in the ABL model are depicted in Figure 3: roughness, roughness + displacement height and the canopy model of Sogachev [16]. This figure shows the vertical profiles of velocity (left frames) and turbulence intensity (right frames) obtained at the two masts located within the canopy area. While the
Table 3. Normalized mean absolute errors (in %) at the three masts positions examined in this study. Last two columns show the weighted average error $\langle E \rangle$ of masts MP1 and A1.

|       | MP5 | MP1 | A1 | $\langle E_U \rangle$ | $\langle E_I \rangle$ |
|-------|-----|-----|----|----------------------|----------------------|
| $z_0 = 0.4$ | 0.86 | 5.99 | 9.59 | 10.25 | 5.9 | 19.1 | 7.64 | 14.82 |
| $z_0 = 0.4 + d = 10$ | - | - | 7.16 | 5.72 | 5.41 | 18.14 | 6.24 | 12.13 |
| $z_0 = 1.0$ | - | - | 6.35 | 10.47 | 1.47 | 25.56 | 3.8 | 18.25 |
| $z_0 = 1.0 + d = 10$ | - | - | 4.39 | 6.73 | 1.63 | 25.86 | 2.93 | 16.6 |
| Forest model | 0.51 | 4.66 | 3.7 | 7.62 | 2.1 | 18.45 | 2.85 | 13.21 |

Table 3 illustrates the performance of different roughness models at the three masts positions. The forest model performs the best in the MP1 for the velocity profiles (Figure 3a,b), it is conspicuous the improvement of the large-roughness method with $z_0 = 1.0$ m when the displacement height is employed, reducing the $\langle E \rangle$ in 35% in both $U/U_0$ and $I/I_0$ (Table 3). Nevertheless, when comparing only the turbulence intensity, better results are obtained by using a $z_0 = 0.4$ m with the same shift of displacement height. In the case of the A1 mast (Figure 3c,d), the error in the turbulence predicted by all methods is largely over-predicted at higher vertical levels. The turbulence intensity is rather worsened once the displacement height is applied. As expected the largest differences are found at the 40 m sensor level in MP1 mast. However, the differences in the velocity profiles remain up the 118 m sensor.

![Figure 3](image_url). Comparison between measurements and ABL statistics of $U/U_0$ and $I/I_0$ at the MP1(above) and A1(below) mast positions. The plots show the results of the three modelling approaches. The measurement data include the uncertainty bars determined by the standard deviation from the data set used to generate the mean profile.
Regarding the use of the two LAD profiles (depicted in Figure 4), little differences above the forest have been found between the constant and the empirical profile at both the MP1 and A1 masts. Expectedly, the results for the large-roughness method with value of $z_0 = 1.0$ and $d = 10m$ presents large discrepancies close to the ground but a better agreement is found above the 40 m sensor.

**Figure 4.** LAD profiles for the sensitivity analysis (a). Frames b) and c) show the dimensionless velocity and turbulence intensity, respectively, for the MP1 mast.

**Figure 5.** Velocity and turbulence intensity dimensionless values for the north-south lines at 78 m a.g.l. passing through MP1. The topography and canopy-covered portion are shown in the bottom frames.
Major differences between the canopy and large-roughness method can be seen in Figure 5 which draws the line passing through MP1 and follows the north-south transect at 78 m above ground. From this figure it can be noticed the decrease in the dimensionless velocity far beyond the canopy covered terrain as well as an enhanced turbulence production after the MP1 position both caused by the combined effects of canopy and terrain complexity in the downstream direction.

6. Conclusions
A canopy model that accounts for both important ABL processes and the drag effects of nearby canopy vegetation [16] has been implemented in CENER’s CFD tool and validated at the Alaiz test site. Compared to data from three mast positions, the canopy model provides accurate estimations of velocity and turbulence intensity whose predictions lie inside the statistical uncertainty of the measurements. The model has been compared to simpler approaches in which, through large values of roughness length and a zero-plane displacement, it is possible to account for the effects of the forestry.

A classification methodology to generate a validation data set from a site measurement campaign was described. The methodology allows to quantify part of the uncertainty in the validation data which is then used to weight the normalized model’s errors at each mast, providing the overall model’s performance.

According to the weighted average of the errors, the best agreement with the vertical profiles of dimensionless velocity is achieved by the canopy model. The model, in comparison to a simulation that considers the forest only as roughness element \(z_0 = 0.4\) m, brings an error reduction of almost 63%. Similar results for velocity profiles were achieved by the large-roughness method with \(z_0 = 1.0 + d = 10\) m. Despite velocity results, the turbulence intensity is better predicted by the large-roughness and zero-plane displacement method with values \(z_0 = 0.4 + d = 10\) m. This method reduces the error in almost 18% against only considering a \(z_0 = 0.4\) m. Comparatively, the second best agreement is obtained with the canopy model with an error reduction of 11%.

Satisfactory results have been obtained by the large-roughness method, in particular for the velocity profiles, providing a cost-effective solution since convergence of the numerical model is easier to reach. However, the canopy model provides more consistent results because it reduces the uncertainty related to the required calibration of the parameters \(z_0\) and \(d\) in the roughness-based methods as seen in Figure 3. Besides, as pointed out by Lopes de Costa et al. [29], the large-roughness method neglects the information about the propagation of the turbulence which could produce considerable errors in the flow predictions downstream the canopy patch (Figure 5).

While some experimental and numerical works have found canopy morphology to strongly affect wind flow characteristics up to 4 times forest height downwind the forest (e.g. [35]), only small differences have been found in this work between using a constant and a \(z\)-varying \(LAD\) profile (using the same \(LAI\) value). This might be due to the fact that in complex terrain sites, the topography-induced pressured gradients become more important than the forestry in modifying the flow at higher vertical levels.

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