Accuracy quantification of a CFD model in complex site by cross-checking wind measurements

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Abstract. In the present study it is discussed a sensitivity analysis on input parameters of a CFD resource assessment methodology built on top of OpenFOAM 4.1, a well-known open source library for numerical fluid dynamics. RANS are solved for dry uncompressible air, the Atmospheric Boundary Layer is calculated without thermal effects (neutral conditions). It is highlighted how the control of a metric based upon a weighted root mean square error (wRMSE) of the local accelerations (speed ups) can guide the wind analyst in the design of the computational mesh and further numerical settings. Moreover, it will be quantified the wRMSE as a function of the distance to the measurement points. The parameters analysed are the horizontal extension of the model, the horizontal resolution within the refined area, which is covering the layout of the wind farm, three different versions of k-\(\varepsilon\) turbulence closure and the number of directional sectors considered.

1. Objectives
The objective of the present work is to define a metric that can be used to evaluate the uncertainty of the wind resource assessment model, hence to guide the wind analyst to further improve his/her estimations. The chosen metric is a weighted root mean square error (wRMSE), of the sector wise errors \(s_{u_{CFD,i}} - \bar{s}_{u_{i}}\) on speed-ups as in the eq. 1:

\begin{equation}
\text{wRMSE} = \sqrt{\sum_{i=1}^{n_s} [f_i (s_{u_{CFD,i}} - \bar{s}_{u_{i}})^2]}
\end{equation}

\begin{equation}
s_{u_{CFD,i}} = \frac{u_{CFD_{\text{target},i}}}{u_{CFD_{\text{ref},i}}}
\end{equation}

\begin{equation}
\bar{s}_{u_{i}} = \frac{1}{n_{t_{i}}} \sum_{t=1}^{n_{t_{i}}} \frac{u_{\text{target},t,i}}{u_{\text{ref},t,i}}
\end{equation}

\begin{equation}
\hat{\sigma}_{s_{u_{i}}} = \sqrt{\frac{1}{n_{t_{i}} - 1} \sum_{t=1}^{n_{t_{i}}} \left( \frac{u_{\text{target},t,i}}{u_{\text{ref},t,i}} - \bar{s}_{u_{i}} \right)^2}
\end{equation}

Where the wRMSE is calculated, in turn, for each pair of measurement points; considering one as the reference and a second one as the target all the possible combinations are accounted
for in the cross-checking procedure. In the present study, having a total of 4 measurement levels, deployed on three masts, led to 12 combinations of reference-target points.

![Figure 1. Layout of masts (top view) with numbered measurement levels, height in parentheses.](image)

The wind rose at the reference point is discretized with \( ns \) directional sectors, the frequency \( f_i \) is computed at the reference for the \( i \)-th direction, calms are disregarded by filtering-out wind speeds smaller than 2 m/s. The speed-up for the \( i \)-th direction defined in eq. 2 is obtained from the ratio of the horizontal wind speed from the CFD database at the target point divided by the same variable at the reference point. A number \( ns \) of CFD models are run, equal to the number of sectors \( ns \), for a central value of the directional sector, imposed at the inlet(s), therefore the horizontal wind speeds appearing in eq. 2 are obtained by weighting two sets of numerical results, i.e. the wind speeds components are linearly interpolated in order to reconstruct the chosen wind direction at the reference point. The speed-up ratio from the measurements \( su_i \) is instead obtained, as noted in eq. 3 by averaging the concurrent ratios, filtered at reference by wind direction and wind speeds for calms, with the chosen threshold of 2 m/s.

In Figure 2 is given an example of sector wise speed-ups from concurrent measurements and predicted by the CFD model. Once the \( wRMSE \) is computed for each combination of measurement level (considering a complete measurement level formed by at least an anemometer coupled with a wind vane, i.e. capable of measuring both wind speed and direction), a reference and a target, they can be plotted against the distance between sensors. The \( wRMSE \) on the speed-ups defines an estimate of the goodness of the CFD prediction only by considering the magnitude of the velocity vector; while indeed a possible misprediction of the velocity vector at the target point it is also in the direction. In analogy with the \( wRMSE \) on the speed-up it could be defined a metric on the directional shift between reference and target points. In Figure 3 an example of directional shifts, sectorwise, measured and predicted by the CFD.

2. Approach
The Digital Terrain Model of a location in Europe has been loaded from the EU-DEM v1.1 [1], the map of use-of-land from the Corine Land Cover (CLC) 2012; the former with 25m resolution and the latter having a 100m resolution. The EU-DEM is a hybrid product based on SRTM
Figure 2. Example of sectorwise errors on speed-ups (sector width 30°). From reference 3 to target 2. CFD speed-ups (black diamonds) as for eq. 2, speed-ups from measurements (empty diamonds with barred confidence level) the 68% confidence level is estimated by $\pm \hat{\sigma}_{su}$, as for eq. 4; frequencies $f_i$ at reference point (green columns).

Figure 3. Example of sectorwise errors on directional-shifts. From reference 3 to target 2.

and ASTER GDEM data fused by a weighted averaging approach. The statistical validation of EU-DEM v1.0 documents a relatively unbiased (-0.56 meters) overall vertical accuracy of 2.9 meters RMSE, which is fully within the contractual specification of 7m RMSE (European Commission 2009). The upgrade to version 1.1 contains the correction of geo-positioning issues, a reduced number of artefacts and an improved vertical accuracy.

From the use-of-land codes of the CLC it is derived a roughness map, according to a conversion table which has been mainly derived from [3].
Several CFD simulations of the wind are carried out on the area of study, by changing the extension of the model, the resolution and number of directional sectors simulated. The Reynolds-Averaged Navier-Stokes (RANS) equations are therefore integrated over a domain covering the area. The open source library OpenFOAM is used for the purpose. The domain is discretized with a structured grid of hexahedral cells, turbulence is closed with a $k$-$\varepsilon$ model (standard [6], RNG [7] or Realizable [8]), while the steady state RANS for uncompressible flows are integrated with the simpleFoam algorithm; only continuity and momentum equations are solved for this study so there are no thermal effects considered in the CFD models. All equations are firstly solved with a 1$^{st}$ order upwind scheme (bounded Gauss upwind), up to a prescribed level of convergence, and secondly the solution is refined by switching the numerical scheme of the momentum equations to a 2$^{nd}$ order upwind (bounded Gauss linearUpwind grad(U)).

### 2.1. Boundary conditions

The computational domain is bounded on the lowest surface by the terrain’s orography, the upper boundary is a horizontal plane set at an automatically calculated height, function of the terrain complexity, lateral boundaries are vertical planes oriented as the Cartesian directions North-South, West-East. The lateral faces orientation implies that when the simulated wind is blowing from one of the Cartesian directions there is one inlet, one outlet and two no-friction walls; in all the other cases there are two inlets and two outlets.

Analytical expressions for the solved variables are assigned to the inlets, the outlets are set with a hydrostatic distribution of pressure, the upper boundary has a no-friction wall condition. A wall-function for fully-rough regimes is prescribed at terrain adjacent cells. Further information on the model is given in [4, 5].

![Map of DEM](image1.png)

**Figure 4.** Digital Elevation Map (DEM) from EU-DEM v1.1 [1]. White circles indicate the met-masts, black circles the wind turbines.

![Map of ROUGHNESS](image2.png)

**Figure 5.** Roughness map from the Corine Land Cover 2012 [1]. White circles indicate the met-masts, black circles the wind turbines.
3. The methodology
The present study is a sensitivity analysis of CFD models to some of the most important settings: the extension of the model, the turbulence closure of the RANS, the number of wind sectors modeled and the resolution of the computational mesh in the area of interest. Over the area studied there were deployed three met-masts, having respectively 30, 40 and 50m height and sensors mounted at several levels. The three masts were installed at the site with consistent overlapping time, 293 days of concurrent data for the first two masts erected in the area (1 and 2), few months of overlapping between the third mast (3 and 4) and the previous two. The first mast is located in a valley and the wind, by observing the wind-rose, looks quite channelled by it, the second mast is located on the highest part of the valley, almost on a saddle point between a ridge, at south-east, where it’s located the third mast, and a group of mountains on the north-west, with a summit at 1780 m above sea level, see Figure 4 for a top-view of the orography. Two main directions are identified: wind from north-east and from south-west. In turn a measurement point is selected as reference and all the remaining points as predicted ones. The measurements at the prediction points, considered as ground truth, are used to evaluate the CFD error. In this fashion it’s possible to plot the error in predicting the local acceleration, in terms of differences between measured speed ups and predicted by the CFD model. The CFD results are interpolated in order to reproduce the wind direction at reference before computing the speed-ups. In order to have one single metric for couple of measurement points a Root Mean Square Error (wRMSE) is computed against the directional sectors, weighting them by their frequency. It is finally studied how the wRMSE error of the speed-ups varies with the model settings such as the extension of the CFD model, the horizontal resolution and the number of wind sectors modeled. The study is quantifying the accuracy of the CFD model through the chosen metric in order to provide guidelines for future CFD micrositing analysis.

In the Figures 6, 7 and 8 it is shown how the wRMSE of speed-ups varies in the horizontal extrapolation with the distance between measurements and predicted points (targets). The general case in the legend ttt xx yy zz is characterized by a ttt turbulence model, xx directional sectors, yy meters of horizontal resolution, zz kilometers of distance between the refinement area and the frontier of the CFD domain. The refinement area, caracterized by a uniform horizontal grid resolution, includes all turbines and met-masts, framing them with 500 meters; its borders are highlighted in orange in Figures 4 and 5.

4. Results
The run test cases are summarised in Table 1, the varying parameters are: the turbulence model (standard k-ε, SKE; the Re-Normalization Group k-ε, RNG; the Realizable k-ε, Real.) the number of directional sectors (12, 24 or 36); the horizontal resolution in the refinement area; the width of the buffer around the area of refinement.

The wRMSE metric is plotted against the distance between the sensors: in Figure 6 it can be observed how the wRMSE varies in a significant manner with model extension, while in Figure 7 it can be observed how the turbulence closure did not play an important role for the selected project, it has to be emphasized how a finer mesh could generate different scenarios with the three turbulence models. With 100 m of horizontal resolution the RNG and Realizable k-ε gave almost identical results, while a little improvement was observed with the standard k-ε. In Figure 8 it’s instead shown the variation of the chosen metric by changing the number of sectors with which the wind roses is interpolated, and the number of CFD simulations, one per sector. It can be observed as an increasing number of sectors do not improve so much the accuracy of the prediction, with a unexpected tendency of increasing the wRMSE with the number of sectors considered. This result should be investigated further, eventually also by decoupling the number of CFD models and the number of sectors used to discretized the wind roses, i.e. more CFD simulations per directional sector.
Table 1. List of cases run, classified by input parameters.

| Turbulence model | SKE | SKE | SKE | RNG | Real | RNG | Real |
|------------------|-----|-----|-----|-----|------|-----|------|
| Number of sectors| 12  | 12  | 24  | 12  | 12   | 12  | 12   |
| Resolution [m]   | 30  | 100 | 30  | 30  | 30   | 100 | 100  |
| Buffer width [km]| 1.4 | 3   | 1.4 | 3   | 3    | 3   | 3    |

| Turbulence model | RNG | SKE | SKE | SKE | SKE | SKE | SKE | SKE |
|------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Number of sectors| 12  | 12  | 12  | 24  | 36  | 12  | 12  | 12  |
| Resolution [m]   | 100 | 100 | 100 | 100 | 100 | 180 | 100 | 100 |
| Buffer width [km]| 5   | 5   | 7   | 5   | 5   | 11  | 11  | 11  |

Figure 6. Dependence of the metric \( wRMSE \) upon the distance to the reference met-mast. Regression with a parabolic function. Variation with buffer width, i.e. extension of the model.

For this complex site a buffer around the area of interest (the wind farm layout) of 11 km was providing a significant reduction of the target metric to be reduced, the \( wRMSE \). The turbulence models were showing much less impact on the \( wRMSE \) on the speed-ups. It is yet to be investigated a horizontal resolution smaller than 100 m coupled with 11 km of buffer width.

5. Conclusions
The weighted RMSE of CFD speed-ups are evaluated for a number of test cases, providing guidance for future projects in terms of model extension, resolution of the grid, number of sectors to model. The methodology is useful to quantify the accuracy of the CFD model, in predicting the wind speed, and in the design phase of the model to keep the CFD accuracy above
Figure 7. Dependence of the metric $wRMSE$ upon the distance to the reference met-mast. Regression with a parabolic function. Variation with tested turbulence models.

Figure 8. Dependence of the metric $wRMSE$ upon the distance to the reference met-mast. Regression with a parabolic function. Variation with number of sectors.
a minimum requirement. The authors of the present studies retain that the presented approach could allow the quantification of the error of the CFD micro-siting. Moreover, the methodology provides valuable guidance to select the values of the settings in a deterministic way, having as target a desired accuracy, or minimum $wRMSE$. Since the most sensitive parameter has been shown to be the model extension, the search for more accurate prediction should aim at considering even larger domains or nesting with mesoscale models, perhaps the inclusion of the Coriolis effects could also improve the calculations as larger and larger domain are considered. The measurements in this study have not been filtered by thermal effects, e.g. with thermal gradient or Monin-Obukhov length, so, a future approach of the presented methodology it could be improved by considering only measurement near neutral conditions.

Also the introduction of a second metric, based on the directional shift between reference and target points will be very likely object of possible improvements of the methodology.

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