Estimation of turbulence intensity and shear factor for diurnal and nocturnal periods with an URANS flow solver coupled with WRF

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Abstract. Mesoscale results using the WRF model were downscaled from 3 km to 250 m resolution in a one-way coupling with VENTOS®/M. The results were compared against field measurements at one site comprising 4 meteorological masts, each with two sets of cup anemometers and wind vanes. The results showed that the addition of VENTOS®/M to the model chain improved the wind speed RMSE. Regarding the prediction of wind direction ambivalent results were obtained. Special attention was given to the prediction of turbulence intensity, particularly in reproducing its inverse proportionality with increasing wind speed (cf. IEC 61400-1 standard). The typical use of computational models in wind resource assessment, i.e., relying on decoupled methodologies and neutrally-stratified regimes, does not allow the representation of turbulence intensity for all wind speeds. The results obtained with VENTOS®/M were in agreement with the measured turbulence characteristics at both high and low wind speeds. Such was achieved without the coupling of any turbulence related field, relying solely on the turbulence model embedded in VENTOS®/M and its respective wall boundary conditions, based on Monin-Obukhov similarity theory. The behaviour under different stratification regimes was verified by analysing diurnal and nocturnal events separately.

1. Introduction
Methodologies based on model chain consist in using the results from models operating at large domains and coarse scales, to drive models operating at smaller domains and finer resolutions, thus downscaling wind conditions through successive levels of refinement. In wind energy, such methods were initially used for short-term forecasting purposes. The application of model chains for hindcasting arose from the increasing need to have both realistic time series and to virtually map wind conditions at locations where measurements are scarce. Although the model chain is mostly composed of meteorological models, engineering flow solvers have been used to downscale the flow solution to the final resolution level, e.g. [1].

The present work focus on the use of a model chain to predict the turbulence intensity and the wind profile shear factor, characteristics relevant to wind resource assessment. Neutrally-stratified flow solvers employing a steady-state formulation can be used to predict the turbulence intensity for wind speeds above 10 m s⁻¹ [2]. However, these methodologies are unable to reproduce the typical increase in turbulence intensity at lower wind speeds, as portrayed in the IEC 61400-1 international standard.

The model chain was composed of the regional model WRF [3] and the VENTOS®/M flow solver [4]. The former was used to predict the mesoscale flow at 3 km resolutions, driven by final
analyses of the NCEP global model. The mesoscale results were used as boundary conditions for VENTOS\textsuperscript{®}/M, to further downscale the flow field to horizontal resolutions of 250 m at the site of interest. The results from both WRF and VENTOS\textsuperscript{®}/M were compared against field measurements attained during a wind resource campaign.

2. Description of the microscale model

VENTOS\textsuperscript{®}/M is a non-linear pressure-based solver for the unsteady Reynolds averaged Navier-Stokes (URANS) equations, assuming anelastic flow and the Boussinesq approximation,

\begin{equation}
\nabla \cdot (\rho u \bar{u}) = 0,
\end{equation}

\begin{equation}
\frac{\partial}{\partial t} (\rho u \bar{u}) + \nabla \cdot (\rho u \otimes u) = -\nabla \hat{p} + \nabla \cdot \mathbf{z} - 2 \rho u \Omega \times u - \rho u \frac{\partial}{\partial t} \mathbf{g},
\end{equation}

where $\mathbf{u}$ is the averaged velocity field and $\otimes$ is the dyadic product. The fields $\hat{p}$ and $\hat{\mathbf{g}}$ are the average perturbations of pressure and potential temperature relative to an hydrostatic reference state, represented by $\theta_0$ and $\rho_0$, the fluid density. The gravity acceleration vector, $\mathbf{g}$, is assumed constant and pointing downwards. The deviatoric stress tensor, $\mathbf{z}$, is the combination of viscous and turbulent stresses, $\mathbf{z}$ and $\mathbf{z'}$, the latter modelled through an eddy viscosity:

\begin{equation}
\mathbf{z} = \mathbf{z} + \mathbf{z}' = (\mu + \mu_t) (\nabla \bar{u} + \nabla \bar{u}^T) - \rho u \frac{1}{2} k, \quad (3)
\end{equation}

where $\mu$ and $\mu_t$ are the molecular and eddy viscosities, $k$ is the turbulence kinetic energy and subscript $T$ denotes the tensor transpose. The average potential temperature, $\bar{\theta} = \bar{\theta} + \theta_0$, is modelled through the transport equation,

\begin{equation}
\frac{\partial}{\partial t} (\rho u \bar{\theta}) + \nabla \cdot (\rho u \bar{u} \bar{\theta}) = \nabla \cdot \left( \left[ \frac{\lambda}{c_p} + \frac{\mu_t}{\sigma_\theta} \right] \nabla \bar{\theta} \right)
\end{equation}

where $\lambda$ is the thermal diffusivity and $c_p$ is the isobaric specific heat capacity. The turbulent thermal diffusivity is replaced by $\mu_t$ and the turbulent Prandtl number, $\sigma_\theta$, assumed as 1. To close the set of equations, the $k-\epsilon$ model is employed (following the formulation in [5]) by solving two transport equations for the turbulence kinetic energy and its dissipation, $\epsilon$:

\begin{equation}
\frac{\partial}{\partial t} (\rho u k) + \nabla \cdot (\rho u \bar{u} k) = \nabla \cdot \left( \left[ \mu + \frac{\mu_t}{\sigma_k} \right] \nabla k \right) + \mathcal{P}_k - \rho u \epsilon, \quad (5)
\end{equation}

\begin{equation}
\frac{\partial}{\partial t} (\rho u \epsilon) + \nabla \cdot (\rho u \bar{u} \epsilon) = \nabla \cdot \left( \left[ \mu + \frac{\mu_t}{\sigma_\epsilon} \right] \nabla \epsilon \right) + C_{\epsilon 1} \frac{\epsilon}{k} \mathcal{P}_\epsilon - C_{\epsilon 2} \rho u \frac{\epsilon^2}{k}, \quad (6)
\end{equation}

with the eddy viscosity estimated as $\mu_t = \rho_n C_\mu k^2/\epsilon$. The turbulence model constants were the common values for atmospheric flows [6]: $C_\mu = 0.033$, $\sigma_k = 1$, $C_{\epsilon 1} = 1.44$, $C_{\epsilon 2} = 1.92$ and $\sigma_\epsilon = 1.835$. The right-hand side of eqs. (5) and (6) contains the respective diffusive transport, production ($\mathcal{P}_k$ and $\mathcal{P}_\epsilon$), and destruction terms. The generation of turbulence is split into two parts: the production due to mechanical shear, $\mathcal{P}$, and due to buoyant motions, $\mathcal{G}$:

\begin{equation}
\mathcal{P} = \mathbf{z}' : \nabla \bar{u}, \quad \mathcal{G} = \frac{\mathbf{g}}{\theta_0} \cdot \left( \frac{\mu_t}{\sigma_\theta} \nabla \bar{\theta} \right).
\end{equation}

Fundamentally the $k-\epsilon$ model assumes that the flow is turbulent and is not appropriate under conditions of turbulence intermittency or laminar flow. Such may occur if the Richardson flux number, $RF = - \mathcal{G}/\mathcal{P}$, is higher than a critical value, $RF_c$, estimated as 0.25 (see [5]). To avoid numerical problems, flow turbulence is retained even under very stable conditions. Additionally, if $\mathcal{G}$ is negative its value is neglected from the $\mathcal{P}_\epsilon$ term in eq. (6) (cf. [5]). As such:

\begin{equation}
\mathcal{P}_k = \max (\mathcal{P} + \mathcal{G}, (1 - RF_c) \mathcal{P}), \quad \mathcal{P}_\epsilon = \mathcal{P} + \max (\mathcal{G}, 0).
\end{equation}

Further details on the VENTOS\textsuperscript{®}/M code may be found in [4; 7].
3. Set-up of the mesoscale and microscale simulations

3.1. Field measurements

The site is located in the North of Portugal at an elevation of 750 m above mean sea level, being characterized by mountainous terrain. It had four measurement masts operating simultaneously, each equipped with cup anemometers and wind vanes at two different heights. Throughout the text these are labelled as A1, A2, A3 and A4, ordered from the northernmost to the southernmost location. Figure 1 depicts the site orography, represented by the microscale surface grid. At the location of the masts, the ruggedness index (RIX) [8] varies between 15% to 22%.

The main requirement in the selection of the time periods to simulate was to have events with high wind speeds, to verify the ability of VENTOS®/M in reproducing such occurrences. The results presented in this work respect to a simulation run of 15 days in July.

3.2. Regional model simulations

The Weather Research and Forecasting (WRF) model is widely used for numerical weather prediction. The code version was 3.1.2 and further details on the model and its numerical treatment can be found in the WRF technical description [3].

The mesoscale simulations were composed of three nesting levels (Figure 2). The horizontal grid dimensions of each nesting level were 24×44, 43×61 and 46×40 (27, 9 and 3 km of horizontal resolution), ordered from the coarser to the finer level. All domains were composed of 49 vertical layers. The initial and boundary conditions were provided using final analyses of the Global Data Assimilation System (GDAS) from the National Centers for Environmental Prediction (NCEP FNL ds083.2 dataset). The sea surface temperature was set using the real-time global analyses of the National Oceanic and Atmospheric Administration (NOAA RTG_SST dataset). Reanalysis datasets are favoured over operational analysis when the objective is to reconstitute wind characteristics for past events. While this is a possible application for the methodology presented in this work, a second objective was to understand if the WRF-VENTOS®/M model chain can be used for forecasting purposes. Hence, analysis datasets were preferred to reanalysis

![Figure 1](image1.png)

**Figure 1.** Surface grid used in the microscale simulations (within red border). The WRF 3 km grid is shown for comparison (mass centres, un-staggered), represented by the green circles. The vertical scale was exaggerated by a factor of 4.

![Figure 2](image2.png)

**Figure 2.** Set-up of the WRF simulations. Domain d3 is nested inside d2, which is nested inside d1. The grid resolutions are 27, 9 and 3 km for each nesting level.
ones. As the initial conditions to the WRF simulations start from coarser GDAS results, a spin-up time of 24 hours was chosen. The VENTOS®/M simulations started after this period.

The choice on the parameterizations followed the recommendations in [9; 10]. The planetary boundary-layer (PBL) was parameterized using the ACM2 non-local closure. Test runs were made with a set-up based on the Mellor-Yamada-Janjic (MYJ) local closure. The ACM2 set-up performed better as it yielded lower MSE (mean squared error) for both wind speed and direction, with an average improvement of 10% considering the present site and other locations. For a complete description of the WRF set-up refer to [4].

3.3. Microscale model simulations

The surface grid was generated by choosing a centre location and using a geometric progression to expand the mesh from that point to the domain edges. The grid orography was set from a high-resolution map through bi-linear interpolation. For grid nodes located at a distance less than 2.5 km from one of the lateral boundaries, the height was forced to agree with the WRF surface mesh by applying a smoothing function to interpolate between both orography maps.

Figure 1 shows the surface grids for VENTOS®/M and WRF. Other characteristics of the mesh are given in Table 1. At the locations of the four masts, the resolution in the \( x \) and \( y \) directions varies between 166 – 223 m and 243 – 310 m, respectively. The simulations were performed with a time-step of 2 seconds.

3.4. Description of the one-way coupling procedure

Both velocity and temperature fields were interpolated from the WRF results into the VENTOS®/M mesh, using tri-linear interpolation. For grid elements below the first WRF vertical level, wall functions are used to compute \( u \), \( v \) and \( \theta \). Such requires that the Obukhov length, \( L \), is estimated to know both \( u^* \) and \( \theta^* \). This was done by numerically solving:

\[
\frac{(\overline{u} - \overline{u}_w)}{(\overline{u}^2 + \overline{v}^2)} \frac{g}{\bar{h}} = \frac{\ln (\Delta z/z_h) - \psi_h (\Delta z/L) + \psi_h (z_h/L)}{\ln (\Delta z/z_{m0}) - \psi_m (\Delta z/L) + \psi_m (z_{m0}/L)^2},
\]

where \( \overline{u}_w \) is the potential temperature at the ground. The horizontal velocity and potential temperature, \( \overline{u} \), \( \overline{v} \) and \( \overline{\theta} \), are known from the first vertical level of the WRF solution (height \( \Delta z \)). Functions \( \psi_m \) and \( \psi_h \) are the integrated forms of the Businger-Dyer stability functions, with \( z_{m0} \) and \( z_{h0} \) as the respective momentum and heat roughness lengths.

After interpolation into the VENTOS®/M mesh, global mass conservation was enforced by correcting the mass flow at the domain boundaries. Any existing mass imbalance was distributed over the boundaries which compose the domain, weighted by their respective mass flow. The correction was applied by scaling the velocity values normal to the boundary. Although this approach may change the flow speed for multiple boundaries, it was favoured instead of correcting solely at one boundary (e.g. the top), as the scaling factors were smaller (less than 1%).

The interpolated 3D fields of the first WRF result are used as the initial condition of VENTOS®/M. To drive the VENTOS®/M simulation, boundary conditions are updated from the available WRF solutions, communicating only the values for grid elements located at the domain boundaries. The VENTOS®/M flow conditions at the boundaries are constantly updated, linearly interpolating between the two WRF solutions closest to the simulation time.
Table 2. Wind speed error for the mesoscale and microscale forecasts. The skill score (SS) quantifies if there is an improvement of the microscale over the mesoscale results, using the mean squared error (SS = 1 − MSE_{micro}/MSE_{meso}). The BIAS and RMSE values are given in m s^{-1}.

| Mast   | corr. coef. | BIAS | RMSE | corr. coef. | BIAS | RMSE | SS    |
|--------|-------------|------|------|-------------|------|------|-------|
| A1 40m | 0.86        | -1.73| 2.60 | 0.87        | 0.89 | 2.23 | 0.26  |
| A1 60m | 0.87        | -1.67| 2.63 | 0.89        | 0.64 | 2.13 | 0.34  |
| A2 30m | 0.86        | -1.49| 2.38 | 0.89        | 0.88 | 2.05 | 0.25  |
| A2 60m | 0.88        | -1.31| 2.23 | [0.89]      | 0.69 | 2.05 | 0.16  |
| A3 20m | [1.88]      | 2.26 | 2.23 | [3.82]      | 0.31 | 2.26 | 0.38  |
| A3 40m | 0.86        | -1.71| 2.59 | 0.87        | [0.19]| 1.90 | [0.12]| 0.22 |
| A4 30m | 0.90        | -1.71| 2.59 | 0.88        | 0.28 | 1.99 | 0.18  |
| A4 60m | [0.01]      | -1.20| 2.20 | [0.01]      | 0.27 | 0.02 | 1.03  |

Avg.  0.87  -1.52  2.47  0.87  0.55  2.12  0.25  
Std.   0.02  0.27  0.24  0.02  0.27  0.13  0.14  

Note: best values are shown in a solid line box, worst values are shown in a dashed line box.

Stratification is imposed by the surface heat flux, q_w, obtained through bi-linear interpolation from the WRF field. The Obukhov length, L, is computed by numerically solving:

\[
\frac{\|u\|}{\kappa} \ln(\Delta z/z_m) - \bar{\psi}_m (\Delta z/L) + \bar{\psi}_m (z_m/L)^3 + g \frac{\kappa q_w L}{\theta_H \rho c_p} = 0, \tag{10}
\]

where \(u\) is the tangential velocity at the control volumes adjacent to the wall, \(\Delta z\) is the distance to the wall and \(\kappa\) is the von Kármán constant (\(\kappa = 0.4\)). Such boundary condition may yield two solutions for \(L\) in stably-stratified conditions [11]. While one of these corresponds to a continuously turbulent regime, the other leads to a collapse of turbulence where both laminar and turbulent states may exist. As such, the root-finding algorithm is bounded to force for a continuously turbulent solution.

Regarding the \(k\), \(\epsilon\) and \(\mu_t\) turbulence fields, these are not coupled with the WRF solution. Their initialization is made using idealized profiles and they depend on the turbulence model, eqs. (5;6), and respective boundary conditions [4] based on Monin-Obukhov similarity theory.

4. Analysis of the forecast results

In Table 2 are shown the global errors for simulations with WRF only (mesoscale) and simulations with the WRF-VENTOS®/M coupling (microscale). The inclusion of VENTOS®/M in the model chain improved the wind speed prediction at 7 of the 8 anemometer locations, with SS values around 0.25. At A3 40 m the mesoscale forecast shows lower RMSE, nearly 9% less than the average error. Conversely, the microscale forecast has higher RMSE, resulting in negative SS. The correlation coefficients are similar for both models. The BIAS is negative for the mesoscale results and with magnitudes around \(-1.5 \text{ m s}^{-1}\), whereas the microscale returns positive values, lower than \(1 \text{ m s}^{-1}\).

Figure 3 shows the time series of wind speed and direction for A1. As the time sampling differs (30 minutes for WRF, 10 minutes for field measurements and VENTOS®/M), the time series were resampled to have 1 hour averages. The microscale model predicts higher wind speeds than WRF. For both locations, there is a good agreement with the microscale for wind speeds higher than \(12 \text{ m s}^{-1}\), not reproduced by the mesoscale. Although the trends imposed by the mesoscale are followed by the microscale, the latter is not merely a noisier version of the former.
The increase in variance, however, also yields error as there are peaks where the forecast over- and under-shoots, producing high mismatches in the squared deviations.

The wind direction time series show variations occurring on a daily basis, between northeast wind during night and northwest winds in the afternoon. This is due to the interaction between the synoptic wind (northeast) and the regional scale sea breeze (west), which is the typical Portuguese summer wind regime. Qualitatively, both direction forecast curves are close to the measured values. When there is a shift in direction, the microscale response has some over-shoot, unlike the mesoscale prediction. Quantifying for all masts (not shown), WRF fared better with lower BIAS (−4° vs. 10°) and RMSE (44° vs. 49°). The SS varied from −1.46 to 0.22, with an average value of −0.36 (SS > 0 at masts A4 and A3 20 m).

4.1. Prediction of turbulence intensity

The turbulence intensity, TI, of the VENTOS®/M simulation results was estimated using two measures: (i) the turbulence kinetic energy field, \(k\), to estimate the variance of the longitudinal component, \(\sigma_u^2\); and (ii) the variance of the horizontal velocity magnitude, \(\sigma_V^2\). Both values were averaged to the integration time of the measurements [4]. Whilst the former is commonly used to estimate TI, the latter is more consistent with the quantity being measured by cup anemometers. From these, two estimates for TI were established:

\[
\sqrt{k^{2/3}/V} \leq TI \leq \sigma_V/V,
\]

(11)

where \(V\) is the mean horizontal wind speed. The value of TI is expected to lie within these

**Figure 3.** Time series of wind speed and direction of the mesoscale and microscale forecasts, together with the field measurements, for mast A1 at 60 m height.

**Figure 4.** Time series of turbulence intensity. The microscale results are shown in the coloured interval, using two different estimates for the standard deviation of the wind speed (A1 60 m).
limits, depending on the value of the average wind speed and variances in the longitudinal and spanwise directions. Regarding the WRF simulations, as the ACM2 non-local closure was used there was no prediction of TI due to the lack of a $k$ field.

Figure 4 shows the time series of TI at mast A1. The microscale results are shown in a coloured interval, representing the limits set in eq. (11). A reasonable agreement is obtained as some events are being captured by the microscale, despite some phase error. The last 6 days of simulation show more discrepancies. Considering all anemometers, the average RMSE for TI is 16% (in units of TI) with a positive bias of 4%, when using $\sigma_V$ to compute TI. For a TI curve based on $\sqrt[2/3]{k}$, the bias becomes −2% with a RMSE of 14%, which is in agreement with the order in which the limits of eq. (11) are placed.

Figure 5 displays TI as function of the wind speed, where the observed data was arranged into 1 m s$^{-1}$ wind speed bins. Each bin shows a box-plot with: (i) the median (black horizontal line); (ii) the interquartile range, IQR (75$^{th}$ – 25$^{th}$ percentile, wide box); (iii) the maximum and minimum values excluding records above the 75$^{th}$ percentile plus 1.5 IQR and below the 25$^{th}$ percentile minus 1.5 IQR (thin box). The data was further grouped into diurnal and nocturnal periods, for which the average TI was computed for each bin, shown by the red and blue lines.

When shown as function of the wind speed, the TI exhibits an inverse proportionality trend. For high speeds both diurnal and nocturnal curves converge to the same asymptotic value. Such behaviour is similar to the neutral flow results in [2]. As the horizontal wind speed increases, the influence of buoyancy decreases. At low wind speeds the diurnal and nocturnal curves differ, the latter being characterized by lower TI. Such is in agreement with the expected behaviour for the typical diurnal and nocturnal boundary-layers. In a convective boundary-layer, buoyancy contributes to turbulence production, increasing the TI. Conversely, in stably-stratified boundary-layers turbulence is dampened by buoyant restoring forces.

The general trend showed in the measurements is well reproduced by the simulations. Overall, the diurnal period shows better agreement than the nocturnal period. The simulations over-predict the nocturnal TI values for low wind speeds, which may happen due to: (i) the $k - \epsilon$ model assumption of high Reynolds number flow, and (ii) the wall boundary condition of imposed heat flux which, under stable stratification, allows for two solutions of $L$. To satisfy the $k - \epsilon$ model requirements, the chosen solution for $L$ represents a continuous turbulence regime [11]. This restrains the microscale model to reproduce phenomena in moderately to extreme stable conditions, where actual turbulence is characterized by intermittency.

![Figure 5](https://example.com/figure5.png)

**Figure 5.** Turbulence intensity TI as function of the wind speed. The raw data is displayed using box-plots (see accompanying text). The red and blue colours refer to diurnal and nocturnal events, respectively. The TI average for each bin is shown by the solid curves. The coloured interval refer to the microscale results, using the limits imposed by eq. (11).
4.2. Prediction of the shear factor

Figure 6 shows the shear factor, $\alpha$, as function of the wind speed, in a similar way as Figure 5. The shear factor is a measure of the velocity profile steepness based on a power law wind profile. It was computed using the two heights levels available for each mast, as

$$\alpha = \ln \left( \frac{V(\Delta z_2)}{V(\Delta z_1)} \right) / \ln \left( \frac{\Delta z_2}{\Delta z_1} \right), \quad (12)$$

with $V(\Delta z_1)$ and $V(\Delta z_2)$ as the wind speed at the two height levels, $\Delta z_1$ and $\Delta z_2$.

Apart from mast A1, the microscale shows better agreement with the measurements for high wind speeds, in the range between 5 to 15 m s$^{-1}$. The mesoscale over-predicts the $\alpha$, particularly in nocturnal situations. As nocturnal periods are characterized by stable stratification, the values for $\alpha$ are expected to increase. This is in agreement with the tendency shown by the measurements and simulation results. For low wind speeds (< 5 m s$^{-1}$) the agreement vanishes as the interquartile range increases. The measured $\alpha$ oscillates, shooting into values of high magnitude, generally of negative sign.

4.3. Results from a neutrally-stratified one-way coupling

With numerical simulations of neutral flow made employing a steady-state formulation [2], the predicted TI does not reproduces the curves in Figure 5. Instead, the results are characterized by a nearly constant value of TI, independent of the wind speed, representative of the flow at high Reynolds numbers. Such results would be sensitive, however, to the wind direction, as the flow field may vary significantly.

To separate the influence of stratification from unsteady effects, the WRF results were used to drive a one-way coupling, but assuming neutrally-stratified conditions instead. The objective was
to understand if the increase in TI for low wind speeds could be reproduced with a neutral flow assumption. Figure 7 shows the respective time series of wind speed and direction for mast A1. The lack of stratification produces unsatisfactory results. There are disagreements happening during both diurnal and nocturnal situations, albeit the latter are more severe. Quantifying for all masts, the SS varied between $-0.3$ and $-2.4$ with RMSE between 3.0 to 4.1, m s$^{-1}$.

Figure 8 shows that the results present an increase in TI for low wind speeds. However, the distinction between the diurnal and nocturnal patches is small. The slope of both patches is similar, conversely to what is shown by the measurements. An hypothesis for the differences with steady-state neutral results exhibiting constant TI [2] may be related with the flow unsteadiness, as it allows for the advection of turbulence into zones where shear production is low (due to low wind speeds). Despite this, stratification effects are paramount to have a satisfactory flow prediction and to reproduce how the TI curves differ from day to night. The shear factor, shown in Figure 9, is more similar to the steady-state neutral flow results in [2], i.e., the predicted values for $\alpha$ are mostly insensitive to the wind speed, unlike the stratified results in Figure 6.

5. Conclusions
The wind flow over a mountainous site was numerically simulated using a model chain comprising of GDAS analyses, the WRF regional model (27 to 3 km) and the VENTOS®/M model (250 m). The simulation was run continuously for 15 days of July, using the WRF results to supply velocity, temperature and surface heat flux boundary conditions.

A comparison with field measurements was made using 4 meteorological masts, each with

Figure 7. Coupling assuming neutral flow (microscale): time series of wind speed and direction.

Figure 8. Coupling assuming neutral flow: turbulence intensity, TI, as function of the wind speed. Refer to Figure 5 for details.

Figure 9. Coupling assuming neutral flow: shear factor, $\alpha$, as function of the wind speed. Refer to Figure 9 for details.
instruments at two height levels. The inclusion of VENTOS\textsuperscript{R}/M to the model chain decreased
the wind speed bias magnitude and mean squared error, yielding an average improvement of
25\%. Regarding the wind direction, the quality of the WRF results was very good, with 10\%
smaller root mean squared error (around 5\(^\circ\)) than the VENTOS\textsuperscript{R}/M prediction.

For turbulence intensity, a reasonable agreement was obtained between VENTOS\textsuperscript{R}/M and
the variance measured by the cup anemometers. All results showed a realistic decay trend with
the wind speed increase, converging to similar values. The agreement in nocturnal periods was
worse, attributed to the limitations of the turbulence model to operate under strong stably
stratified conditions.

The agreement for the shear factor varied. For wind speeds higher than 5 m s\(^{-1}\), comparing the
average values predicted by WRF and VENTOS\textsuperscript{R}/M, the latter was closer to the measurements
for 3 of the 4 masts. At low wind speeds the agreement vanishes as the variability of the
measured shear factor increases.

A different set of simulations was made using the same model chain, but assuming neutral
stratification in VENTOS\textsuperscript{R}/M. The quality of the results was deemed unsatisfactory, both
for mean and turbulent flow fields. An inverse proportionality trend was obtained between
turbulence intensity and wind speed, but with few differences between diurnal and nocturnal
events and high over-predictions. Such results show that stratification modelling is paramount
for methodologies based on model chains with dynamic coupling, in order to reproduce the
characteristics of the flow.

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