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Assessment of wind fields over forested sites with LES and a nacelle lidar

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Abstract. The capability of a model based on Large-Eddy Simulations (LES) to reproduce turbulence measurements over a forest of heterogeneous density is assessed. Measurements are obtained from an experimental campaign with a continuous wave lidar mounted on the nacelle of a wind turbine (not considered in this work) that scans over a cone in the upstream direction. The measurements are then compared with the results of the LES of the atmospheric boundary layer in neutral stability conditions. The model comprises a full description of the forest over a large area upstream of the lidar by using plant area density data obtained with airborne laser scans, which also provides the terrain elevation. Although the relatively restricted mesh refinement of the LES leads to a limited representation of turbulence towards higher frequencies, comparisons with the measurements show that the model is capable of reproducing the turbulence levels and spatial coherence in the hypothetical rotor plane. Results permit to conclude that the LES-based model is a suitable tool to identify and predict the microscale effects that terrain features have in the wind resource for sites of high complexity. This work exemplifies the challenges associated to the process and interpretation of data from the employed lidar and its setup, for which a filtering technique potentially useful in future studies is presented.

1. Introduction

As wind parks are built in remote locations, there is a growing prospect that these will be located on areas that represent a bigger challenge for the wind resource assessment, such as complex terrain and forested regions. Large-Eddy Simulations (LES) represent an suitable option to predict site specific wind conditions due to the capacity to reproduce transient flow features, unlike other averaged flow solution methods like Reynolds-Averaged Navier-Stokes (RANS). LES has previously proved to be a suitable tool for studies of single wakes, complete farms or features arising from the terrain complexity [1, 2, 3, 4]. The development of LES models adequate for regions of non-homogeneous forest over complex terrain requires validation by comparing with experimental data. Conventionally, different measurement equipment is installed along a metmast which besides the steep investment, is limited with respect to the spatial distribution that the recordings can provide. In this regard, remote sensing instruments such as lidar systems can contribute to alleviate these issues. Lidars are increasingly used and have become a practical and important tool at various stages of wind projects. The two most common types of commercially available lidars used for wind energy purposes are 1) pulse-based device lasers that record simultaneously the Doppler returns at a few points along a beam, repeating the process along a few paths [12] and 2) continuous wave lidars where a laser focuses
on a point, fixed or moving, for different ranges. Both types of devices can be set on the ground—as wind profilers—or mounted on the nacelle of a turbine, either to measure the incoming wind or pointing downstream to map the wake field. In the most basic application, these devices are used as anemometers dedicated to optimize the power extraction but they have also seen use in research applications [6, 7, 2, 8]. Despite some limitations [9, 8], their use to study wind turbulence is very apparent. Precisely, with larger rotors placed in complex, forested terrain, there is a need for investigations of load assessment and load mitigation. While the option of employing nacelle mounted lidars for these applications is very attractive, there are practical issues that require further examination to solve. Particular examples of these are the assessment of measurement uncertainty, how to modify the controller system to make an optimal usage of the lidar measurements and how to detect turbulent eddies coming to a yawed turbine.

In this work, we used raw data obtained from a forward-looking, nacelle-mounted continuous wave, conically scanning lidar and employ it in the validation of a LES model developed to reproduce the wind flow and in particular, the turbulence features arising from the forest and terrain complexity at a site in Sweden. This location is selected as it exemplifies the characteristics of remote locations that are increasingly considered for the development of wind projects in the country. Make note that parts of the results obtained with the current LES model have been presented previously in a technical report [5]. This work is divided in the following parts: Sec. 2 describes the measurement campaign as well as the process of data collection, filtering and post-processing. Sec. 3 presents the implementation to model the forest in the LES next to the numerical setup employed in the computations. The results and discussion are presented in Sec. 4 followed by the conclusions.

2. Measurement campaign and processing of data

The measurements were made at a wind farm located over a mild-complex terrain covered with a non-homogeneous forest in an undisclosed location in Sweden. A nacelle-mounted continuous wave, conically scanning lidar was used to measure the velocity in the Line-Of-Sight (LOS) direction $u_r$ upstream of the rotor at 50 points distributed over a circular scan, completed in one second. The lidar was mounted at a height above the ground of 101.5 m (measured at the axis of the scanning cone) on a wind turbine with a hub height at 98.5 m. The opening angle $\phi$ of the scanning cone is 30 degrees. Data used in this work consists of two different measurement periods. A first period, when the wind speed was measured at the upstream distances of 10 m, 108 m, 211 m and 300 m for about two months and a second, with measurements at 10 and 200 m upstream, also for about two months [5]. For the first period, the beam made 60 revolutions for the 10 m range and 180 revolutions for the other ones, yielding a separation of 3 min between the recordings at every range. That period has been used to compare the velocity distributions of the lidar to those of the LES. The other period made 9 minutes of continuous measurements at 200 m distance, alternated with 5 seconds of measurements at 10 m distance. The second period has been used to compare the spectral coherences of the lidar with those of the LES.

The wind direction for the study is chosen along a direction free from wakes of other wind turbines located around the lidar, using the recorded position of the nacelle within the SCADA data. This was selected based on the 30 minute mean wind direction coming from the wind sector $255 \pm 12.5$ degrees. The measurements used in this work were taken between December 2015 and March 2016 for the first period, and between April and June 2016 for the second period. More information about the measurement campaign can be found in [5].

The velocity $u_r$ is estimated from the Fast Fourier Transformed (FFT) backscatter signal and beam angle recorded by the lidar. The raw records comprise data of $u_r$ estimated according to an algorithm created by the manufacturer, which was used to calculate the velocity distributions. Two different approaches are normally used for these analyzes. In the first one, the velocity distributions are obtained from averaging the Doppler spectra, which was shown by [10] to yield
better estimates of the true shape the velocity distributions in comparison to the second method, where the same distribution is recreated from high frequency \( u_r \) estimates. The fact that the first method yields better estimates is due to the retention of high frequency fluctuations. However, as pointed out in [12], gradients of velocity within the measurement volume will widen the Doppler spectra, an effect not present in the first approach which only studied a homogeneous direction [10]. Furthermore, the increment in measurement volume of continuous wave lidars can be substantial for large distances, so the one at 100 m (~50 m above forest, where 50% of the backscatter is expected to come from within \( \pm 9 \) m) is noticeably different from that at 200 m (~25 m above forest, where 50% of the backscatter is expected to come from within \( \pm 35 \) m) [11]. During the analysis of the measurements both methods have been tested. This experience demonstrated that the use of the manufacturer’s algorithm produces less sensitivity to measurement error, thus providing smoother velocity distributions that also showed wind profiles with less indications of measurement error (such as the negative wind shear). These advantages favoured the use of such method, which was then used for comparison of velocity distributions. The averaging volume is also considered when sampling velocities in the LES, in an effort to compare quantities affected by a similar spatial spread, see Sec. 3.4.

When following the previous approach to obtain the experimental values, it was found that the internal algorithm was neglecting a sizeable portion \( u_r \) estimates, possibly due to bad signal to noise ratio or to non-Gaussian velocity distributions. Therefore, in order to keep velocity time series with a sufficiently high frequency as to produce cross-spectral statistics, a routine was developed that would provide more frequent \( u_r \) estimates. It consists of the following steps:

- Divide the circumference of the scan on 12 equidistant sectors, 30 degrees width.
- For each revolution, average the (FFT) spectra for all returns within each sector.
- Remove all backscatter for frequencies corresponding to wind speeds below 1.65 m/s to discard the returns during blade passage and all backscatter below 4 times the background noise.
- Calculate the centroid of the average spectrum and the standard deviation \( \sigma \) as the rms of the deviations from the centroid.
- Repeat the previous step, but only for data \( \pm 2 \sigma \) from the centroid values. The final centroid value is saved as \( u_r \) with a corresponding \( \sigma_{u_r} \).

Although the last step removes \( \sim 1.5\% \) of the original variance of the measurement (if the shape is Gaussian) it does remove a good part of the noise at high frequencies, corresponding to unlikely high wind speeds, which otherwise influence the computation of \( u_r \). It should be remarked that signal-to-noise ratio is appreciably different around the scanning circle, yielding higher retention data rates for the upper positions in the scanning circle. For instance, while 69% of data was kept for the top position, only 4% can be used from the bottom location (nearest to the ground) for the case of 200 m upstream.

Data is also filtered so only measurements acquired in neutral stability are used in the comparison. In the absence of meteorological data, simple considerations with regard to the elevation angle of the sun are used. Specifically, only times with elevation angles between 10° and 30° with the purpose of filtering out the very stable data of negative elevation angles as well as attempting to isolate transition periods between the stable conditions at night and the unstable conditions during the day. An additional requirement of wind wind speed at lidar height exceeding 5 m/s was also used. The ability of this method to filter for neutral conditions was tested by using data from a similar site in southern Sweden [13] (not shown in this work). When compared to six different stability classes as well as a class containing all data, it was found to successfully filter out neutral conditions.

In order to calculate spectral coherences, an evenly spaced time series of 1 Hz is constructed from the \( u_r \) estimates described by the routine above by means of linear interpolation. In these
calculations, no 30 minute period with interpolation sections longer than 15 seconds are used. Finally, for the analysis of wind profiles and wind speed distributions, wind speeds at all heights were scaled by $\bar{u}$ from hub height for each 10 minute period. This was done to maximize the amount of measurement data, also achieved by removing the effect of distribution widening that would otherwise occur for the ensemble averaged distribution. A minimum threshold of $u_r > 4$ m/s at hub height was included for the data selection.

3. Flow model

3.1. Model description

The flow model is based on LES and is implemented on the OpenFOAM® platform [15], version 3.0.1 (the OpenFOAM Foundation Ltd, London, UK). The Sub-Grid Scale (SGS) model [16, 17] estimates the subgrid viscosity $\nu_{SGS}$ by means of a transport equation for the subgrid turbulence kinetic energy $k_{SGS}$. To model forest drag, it is assumed that the forest acts as a porous surface extracting momentum from the flow. This translates into a source term introduced in the LES momentum equation:

$$f_{D,i} = -C_D a |\langle u \rangle| \langle u_i \rangle$$

where $C_D$ is the forest drag coefficient, $a$ is the frontal-area-density (considered here equal to the Plant-Area-Density, PAD). Filtered (or resolved) quantities in the LES are denoted with $\langle \cdot \rangle$ while wind velocities $u_i$ are defined in directions $i = 1, 2, 3$ equivalent to the longitudinal, crosswise and vertical components of the vector $\mathbf{u}$ in the reference frame of the grid. This method to represent the forest has been used by [18] and [19] to model flows over forests with good results. As in the latter work, $C_D = 0.2$ is employed here. While eq. (1) represents the effect of the forest in the resolved part of the velocity field, its effect on the subgrid part consists of an increase in the dissipation of the subgrid turbulence kinetic energy. This is accounted by adding a term to the transport equation of $k_{SGS}$:

$$\varepsilon_{SGS} = -\frac{8}{3} C_D a |\langle u \rangle| k_{SGS}.$$  

It is desired that the model accounts for the interaction of the wind with the terrain in the parts without forest or with very low forest density. For this reason, a wall model is used where the velocity deficit is computed indirectly through the application of a surface stress. Such method is described by Schumann [21]. An implementation of this wall model is available within the SOWFA package [22] so the corresponding library is imported into the OpenFOAM implementation used in this work. This model has been used in previous works providing good results in estimations of the wind flow over non-homogeneous forest in complex terrain. This and other details of the model can be found in [4], [5] and [20].

3.2. Numerical setup

The domain consists of a box with dimensions $L_x \times L_y \times L_z = 16.48$ km $\times 5.15$ km $\times \sim 1.2$ km in the longitudinal, spanwise and vertical directions (which varies due to the changing elevation of the terrain). The location of the lidar in the domain corresponds to $d_{Zeph,x} = 12.875$ km, in the mid-spanwise direction. The longitudinal direction of the domain is aligned with the wind direction, at 255 degrees. The grid is created with the mesh generator created by [23] which reproduces the elevation of the terrain at the bottom surface. This tool allows to create a mesh with 3 regions in the horizontal plane of varying refinement. This can be seen in Fig. 2, which also shows the ground elevation in the computational domain. There, the innermost region of the domain is outlined with a dashed line and measures $\ell_{f,x} \times \ell_{f,y} = 5.665$ km $\times 2.06$ km. This corresponds to the largest refinement, where the cell size is $\Delta x = \Delta y = 10$ m. Outside this
region the cells are uniformly stretched towards an edge perimeter of width $\ell_b = 515\, \text{m}$ with cell size $\Delta x = \Delta y = 50\, \text{m}$. This boundary serves as a smoothing zone for the topography, so the elevation differences are reduced until an uniform height of 155 m is reached, corresponding to the average elevation at the inner border of the buffer. This feature is necessary as periodic boundary conditions are used in all sides of the domain. In the vertical direction, the height of the first cell is $\Delta z \sim 4\, \text{m}$ at the location of the virtual lidar and increases with an average rate of $\sim 1.04$. These values are approximate as the terrain-following layers (98 cells in the vertical direction) become increasingly flat towards the top boundary, set at the uniform height of 1210 m. In total, the grid is composed approximately $29.55 \times 10^6$ cells.

3.3. Forest and terrain data

Airborne Laser Scans, ALS were obtained from the mapping agency of the Swedish government (Lantmäteriet). These consists of high-resolution backscatter data from an airborne lidar and carries information of the 3D coordinates of the sampled point and the reflected intensity. The PAD are calculated following the method of [24] but with a weight of each reflection corresponding to the fraction of return intensity out of the total return intensity of the given beam. This is done with the purpose of accounting for higher order return points of the beam, unlike the previous approach that considers only the first return. Following this method, the points are mapped in a grid of $10\, \text{m} \times 10\, \text{m} \times 1\, \text{m}$ in the north, east and vertical direction. The ground height represents the median altitude of ground reflections within each cell. Fig. 1 shows the map created with this method, showing also the wind sector ($\pm 10$ degrees) where measurement data is gathered for this work.

![Figure 1](image.png)

**Figure 1.** Tree height derived from the ALS. The sector chosen used in the study is highlighted in color, with the lidar located at the origin (white circle).

The PAD generated with the above procedure is imported into the computational domain via a linear interpolation between the generated maps and the local resolution in the domain. At the buffer region, a constant tree height of 11.5 m (the average tree height in the domain) and a $\text{PAD} = 0.16\, \text{1/m}$ (yielding a plant-area-index of $\approx 3$) is used.

The flow is driven by a uniform pressure gradient following a procedure described by [25] that comprises the introduction of Coriolis forcing (assuming a latitude of 58 degrees). The pressure gradient is imposed in function of a geostrophic wind velocity of magnitude $u_g = 10.5\, \text{m/s}$ at the top boundary, which in turn would yield the desired mean velocity of approximately $7\, \text{m/s}$ and direction $255^\circ$ at the lidar position. The complete height of the ABL is simulated to avoid the parametrization of the components of the shear stress, as they become negligible above approximately 1 km. The ground surface is set to a wall with a uniform roughness of $z_0 = 0.03$
Figure 2. Terrain elevation at the bottom surface of the computational domain. The mesh regions and the position of the lidar (circle). Incoming wind direction is 255 degrees at the height of the lidar, corresponding to the $x-$direction of the domain.

m. The PISO algorithm is employed for the solution of the pressure-velocity equations, while the backwards interpolation scheme is applied in the solution of the transient term, next to central differences for the remaining terms. Simulations are run for about $120 \times 10^3$ s to develop the flow and attain second-order statistical convergence. Results are obtained during a subsequent computation lasting $20 \times 10^3$ s with $\Delta t = 0.24$ s. This yields a maximum Courant-Friedrichs-Lewy number of 0.67 over the whole domain.

3.4. Virtual lidar from the LES
Time series were stored from the LES at 100 m and 200 m upstream from the lidar for the 12 positions corresponding to the 12 sectors of the lidar scan. This corresponds to the same two scanning circles of radius $200 \tan(\phi/2) \approx 54$ m and $100 \tan(\phi/2) \approx 27$ m that is measured by the lidar. The probe volume was accounted for by a weighted average over three grid cells, using weights from a standard function of the probe volume for continuous wave lidar [12]. In the case of 200 m upstream, 50 % of the measurement volume lies within $\pm 35$ m which means that the measurement length is somewhat underestimated in the lidar. The wind vectors were then rotated to the lidar coordinate system so $u_r$ can be estimated and compared directly to the measurements. This output will be referred to as the virtual lidar.

4. Results and discussion
4.1. Wind profile
The measured and simulated wind speeds are shown in Fig. 3. As described in Sec. 2, a filter for the elevation angle of the sun being between 10 and 30 degrees was used as a proxy for neutral conditions. The shear of the measured profile was in fact a strong function of the solar elevation angle, as well as the width of the velocity distributions (not shown). However, for this selection criteria, the measured and simulated wind profiles agree to a reasonable extent. For the first measurement period, between December and March, the lowest measurement height has a negative shear, for which the reason is unknown. Some type of measurement error is likely the cause. This is also manifested on the velocity distributions, as shown below.

The wind profiles from the lidar measurements and virtual lidar from LES were made using
the approximation $u \approx u_r / \cos(\phi/2)$ which assumes that there is no systematic effect from turbulence moving the distribution to higher or lower values and that the centre point of the lidar is aimed towards the mean wind direction. Also shown is the mean wind speed profile from virtual masts in the LES at 100 m and 200 m upstream. There is a close agreement of the virtual lidar and the virtual mast profiles. The lidar measurements show a larger difference in wind speed between the two sides of the scanning circle (up to 0.4 m/s as opposed to maximum 0.1 m/s for the virtual lidar). Assuming the wind field is homogeneous, this difference can be used to calculate the potential yaw misalignment $\gamma$ of a turbine relative to the mean wind direction. Notably, the measurements indeed show a systematic difference between the two sides of the scanning cones which would indicate a yaw misalignment of 4° (profile at 200 m) to 9° (profile at 108 m) although this could be due to other reasons, such as misalignment of the lidar itself or measurement errors. Due to veer in the wind profile from the Coriolis effect, some parts of the rotor plane are bound to be misaligned with the direction of the mean flow. This is visible in the LES data as a crossing of the wind profiles from the left an right sides of the scanning cone, at approximately the hub height. In the measurements, this effect is seen as a larger difference between the left and right part of the scan above and below $z_{hub}$.

4.2. Velocity distributions
In addition to compare radial wind speeds, the Rotor Equivalent Wind Speed (REWS) was also computed from both the lidar and the LES. The REWS was obtained by splitting the rotor area in six different sections according to the following equation,

$$REWS = \left( \sum_{i=1}^{6} u_i^3 \frac{A_i}{A} \right)^{1/3}$$

where $A_i$ is the rotor area covered be each section and $A$ is the total rotor area. REWS was only calculated for the part of the measurement campaign that measured predominately at 200 m and the frequencies containing the main part of the REWS energy were not fully covered by the short measurement cycles in the other part of the campaign. The distribution of REWS and radial wind speeds based on both LES and measurements can be seen in Fig. 4. The scaling
Figure 4. The outer circle shows the probability distributions of $u_r$ for each of the 12 sectors at 200 m upstream (blue) and 100 m upstream (red) from lidar (full lines) and LES (dashed-dotted lines). The centre plot shows the distribution of REWS.

ensures that the radial mean wind speed at hub height is matched by the observations, but from the figure it can be seen that the width of the distribution is slightly lower in the LES. The missing part could correspond to fluctuations that would take place in the subgrid scales, so an underestimation in the resolved part of the LES is expected. For the hub height, there is a very close similarity between the distributions at 100 m and 200 m upstream in both simulations and measurements. Elsewhere, the width of the distribution does not change particularly with height, indicating that variance is only weakly decreasing with height. Since the distributions are based on $u_r$ estimates from measurement volume average, we do not expect any significant effect from velocity gradients within the measurement volume. With distributions made from averaged Doppler spectra, a larger widening would have been expected in the vertical directions than the horizontal (where $u_r$ is not a function of measurement distance). The lowest sector (number 6) displays a large width of the measured distribution, for which the cause is unknown, but possibly due to measurement error.

The distribution of the REWS is naturally narrower than the distribution of the LOS data, reflecting the filtering by the rotor average. Interestingly, the measured distribution is much more skewed than the modelled distribution. Since the REWS comprises the average of the cube of the wind, a slight skew towards higher wind speeds is expected. A contribution to the skewness in the measured REWS distribution could result from the influence of the edges of the measurement volume, which would be missing in the virtual lidar.
4.3. Spectral coherence

The spatial coherence of a turbulent wind field is an important property for the total effect of the flow on the turbine, and in fact most nacelle mounted lidars measure the incoming velocity field with a few upstream measurement points, highlighting the need for an accurate estimation of the spatial coherence. In Fig. 5 the spatial coherence is shown for both lateral and vertical separations. Coherences were calculated according to:

\[ \text{Coh}_{i,j}(f) = \frac{|C_{i,j}(f)|}{\sqrt{C_{i,i}(f)C_{j,j}(f)}} \]  

(4)

where \( C_{i,j} \) is the cross spectral density of \( u_r \) for the sectors \( i, j \) at the frequency \( f \). Coherence was calculated for all horizontal and vertical pairs of the 12 sectors previously described. It is important to notice that both measurements and virtual lidar include filtering due to the probe volume. Thus, in the higher frequencies the coherence may be lower than expected for two actual points. For the measurements, the vertical coherence is generally larger than the lateral,

![Figure 5](image_url)

Figure 5. Spatial coherence from the lidar (full lines) and the LES (dashed-dotted lines). The results for lateral separations are shown on the left plots and those of vertical separations on the right. Using clock numbers to denote the sectors (12 corresponding to the uppermost and 6 to the lowermost as in Fig. 4), the lateral coherences are 1-11, 2-10, 3-9, 4-8 and 5-7. For vertical separations 8-10, 7-11, 6-12, 5-1 and 4-2.

except for the uppermost lateral separation, which clearly stands out in both measurement and LES. The difference in coherence between the individual pairs is similar in measurements and
simulation, but the coherence is generally greater in the simulation. The noise contamination of the lidar measurements, together with the need of interpolation of the time series to fill the gaps when sampling is interrupted may bias the measurements towards a lower coherence than the actual wind field. Most of the difference between the simulation and measurements is found at frequencies around 0.002 to 0.008 Hz corresponding to time scales of 2-10 minutes. In a previous publication [20], the same LES was found to agree better with measured coherence for vertical separations in the same frequency range, in controlled neutral conditions, suggesting either measurement uncertainty or uncertainty in the selection of neutral conditions as possible causes.

5. Conclusion
A comparison of flow characteristics from LES and measurements obtained with a nacelle mounted lidar has been presented. LES computations were performed over a large domain, employing a forest density and terrain elevation data obtained from airborne laser scans. This has the purpose of representing the effect of the non-homogeneous forest and topographic variations on the wind flow. In this way, it is possible to eliminate—or at least largely reduce—the representation errors of the surface conditions in the resource assessment. Despite this, it was first observed that the comparison is hindered by the strong effects of atmospheric stratification on the properties of the flow. Since measurements of the stability conditions were absent, a simple selection by solar elevation angle was carried out.

A comparison of the wind profiles showed that similar velocity gradients are obtained in the simulation with respect to the measurements. However, the measurements display a behaviour that could not be explained by flow properties, such as an negative shear of the two lowest points, highlighting difficulties in data quality control. Measurement results of the probability distributions of the line-of-sight velocity show that there is not an appreciable change of the width of the distribution with height, indicating a weak correlation of variance and altitude (except for the lowest sector). The comparison with the model indicates that for the most part, LES was able to reproduce the shape of the distribution. The radial mean is relatively well predicted, although the narrower distributions from the LES point at the scales of fluctuation that are modelled as opposed to being resolved in the simulation. These differences are accentuated in the sector nearest to the forest, where the measurements yield noticeably wider distributions which persisted despite applying different strategies in the data filtering. As a result, this feature of the lidar results is attributed to measurement errors that have not been possible to clearly identify.

Generally, the LES showed higher coherence than the experimental observations, but the interpretation of the results is complicated by the measurement uncertainty and potential differences in the measurement volume. The employed LES model has previously been evaluated against mast measurements with sonic anemometers for vertical coherence, showing a better agreement [20]. A point for further study is whether the difference is due to measurement uncertainty, data selection, or actual difference in flow properties between the sites. While coherence for vertical separation can be calculated using tower measurements, data sets for lateral separation are much rarer. This reveals the need of studies examining cross-spectral characteristics for lateral separation in both LES and measurements over forested terrain.

It was shown in previous studies that in order to reproduce the footprint of the forest and terrain on the flow, it was important to include a large section of the upstream terrain. Therefore, reducing the resolution of the mesh is seen as a compromise to achieve that effect. This entails a reduction in the capacity of the LES to resolve the small-scale fluctuations, which is apparent in the turbulence features compared here. Consequently, the reduction of accuracy in the reproduction of fine scale structure of turbulence is a small concession to accept in order to simulate the impact of the many complex features of the terrain. Considering this, the model can
represent a valuable tool in the assessment of the wind resource. In particular, for the evaluation of the variations of velocity and turbulence levels that arise from complex and forested terrain that increase the loads on wind turbines and affect their production.

Furthermore, this work illustrates some of the challenges in processing and interpreting nacelle-based continuous wave lidar data and presents a processing technique that could potentially be useful for future studies. Similarly, the study exemplifies the difficulty of performing comparisons without adequate measurements of the atmospheric stability and the uncertainty in the difference of probe volume for lidar measurements and virtual lidar. To the same degree, it points towards the need of integrating the representation of atmospheric stratification in the models.

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