Wind energy relevant characteristics of turbulence over boreal forests

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Wind energy relevant characteristics of turbulence over boreal forests

Johan Arnqvist, Hugo Olivares-Espinosa, Ingemar Carlén

Uppsala University, Department of Earth Sciences, Villavägen 16, 752 36 Uppsala, Sweden

E-mail: johan.arnqvist@geo.uu.se

Abstract. Turbulence statistics from three tall meteorological masts and LES in forested landscapes are compared to standard turbulence models used for wind turbine design. The comparison is split into different atmospheric conditions to highlight the impact of stratification on the character of turbulence. The aim of the work is to clarify to which extent standard turbulence models are accurate over forested regions. To this end, different spectral measures such as power spectra and coherence are examined as well as vertical profiles of turbulence characteristics relevant to the design and siting of wind turbines. The measurements are used to investigate vertically separated 2-point statistics and the LES to investigate laterally separated statistics. The results show that in neutral stratification and for smaller separation distances, in the order of half a radius, the standard turbulence models apply, but in non-neutral stratification, particularly in stable conditions and for larger separations the disparity between observations and standard turbulence grow. This effect is mainly attributed to the effect of stratification, while features in the turbulence statistics specifically related to the forest cover is absent at heights relevant to wind energy. The results of the study are expected to be of interest for turbine design purposes as well as wind resource estimation and wind modelling in forested areas.

1. Introduction

Wind power is today commonly installed in forested areas. Despite that on the face of it, the wind resource is limited due to the drag of the trees, mitigating factors still make sites in boreal forests attractive for wind energy. Some of these mitigating factors are; Less visual impact and less social opposition as well as synergies with land owners in managed forests. Furthermore, studies have shown that wind turbine wakes typically are shorter [1]. Still, the design of wind turbines, and later site suitability assessment work, follow standard models that were not originally developed for forested sites [2]. There has been a concern that off-design wind conditions could potentially reduce both output and lifetime of turbines located in forested areas [3, 4]. Subsequently, both inaccurate modelling and uncertainties related to the site roughness has been determined as risk factors for forested sites [5].

In the end of the last century intensive research was conducted to determine how turbulence above vegetation canopies differed from lower vegetation or wall roughness. A summary is provided by Finnigan [6], which concludes that the main difference between wall turbulence and above canopy turbulence is due to mixing-layer effects, where the inflection point in the wind profile at the top of the canopy represents an additional source of turbulence and quasi turbulence motions. While mixing layer effects are thought to be important within the roughness

sublayer, above that layer, 2-3 tree heights over the tree tops, the effects are usually reported as small or diminished in the literature [6, 3, 7]. Other than mixing-layer effects, intermittent turbulence [8, 9], strong shear [3, 1, 10], directional shear and gradients in turbulence magnitudes have been suggested as areas where above forest canopy turbulence might differ from turbulence above other surfaces [3, 7, 9].

The potential effects of real site turbulence being different from design turbulence are multiple. First, structural loads from lift and drag related forces could differ from their expected values [4, 1, 11, 10]. Second, turbulence different than design turbulence could potentially lead to sub-optimal performance of the turbine controller, which in the worst case leads to both lower production and higher loads than necessary [3]. Finally, the power production estimates become less precise since the size and character of the turbulence structures are important for the potentially available wind power in the turbulent fluctuations as well as their effect on wake recovery.

Following on the development of conceptual knowledge on the character of the forest boundary layer in the decades before and after the turn of the millennium, the recent decade has seen a strong development in modelling techniques. In a benchmarking study for simulating winds over forests Ivanell et al. [12] concluded that the technique to use Airborne Laser Scans (ALS) to directly import the forest densities into the model domain [13] greatly reduce the subjectivity compared to the use of roughness lengths, and that this improves accuracy. In this way, the forest is modelled through a drag force formulation as a sink term for momentum and turbulence kinetic energy, k instead of using roughness lengths to represent the drag. At the same time, the study revealed important sensitivity to the values of closure constants for Reynolds Averages Navier Stokes (RANS) models, particularly the value of the C_μ constant in the $k-\epsilon$ closure. It was concluded that models using lower values $C_\mu \approx 0.03$ predicted a more realistic turbulence intensity than those using values for general applications ($C_\mu \approx 0.09$) [14].

Striving to improve the representation of stratification on the forest boundary layer, recent developments has been made extend drag-based models to both stationary non-neutral stratification in Large Eddy Simulations (LES) [15] and RANS [16] as well as non-stationary, non-neutral stratification in Unstable-RANS [17] and LES [18]. Besides the development itself, these studies have pointed to the need for validation data to set model parameters and find the appropriate balance between model resolution and domain size.

Despite the recent advancement of computational fluid dynamics (CFD) tools such as RANS, URANS and LES, load calculations still heavily rely on analytical or semi-analytical tools. The IEC standard [2] stipulates two options to this end. One is a simple approach based on the Kaimal model [19] for the spectral shape, matched with a Davenport model for the vertical and lateral coherence [20]. The other model is the more advanced Mann model [21] that rely on Rapid Distortion Theory (RDT) to model physically consistent synthetic turbulence. While the Kaimal model lack physical coupling between wind components and as such is less sensitive to the effect of stratification, there has been an open question as to what extent the Mann model is accurate over forests in non-neutral stratification. Good agreement with experimental data was shown in [22] and since then the Mann-model has been extended to non-neutral stratification [23, 24, 9]. With respect to validity over forests Mohr et al. [9] revealed a tendency for the Davenport model to overestimate vertical coherence. In a recent study for onshore conditions in neutral stratification Ning [25] showed a weak tendency for the IEC model to overestimate vertical coherence and low heights, but at 140 m the model matched LES from two different models well for both vertical and lateral coherence. How the IEC standard applies for lateral coherence over forests has remained an open question, and also its validity in different stratification.

In order to help clarify to what extent the turbulence over forest canopies differs from the standard turbulence character used to estimate yield and load from wind turbines, this work presents a comparison of standard models of turbulence characteristics to measurements. In

addition to the vertically separated 2-point statistics from the tower data we also compare laterally separated 2-point statistics using Large Eddy Simulations (LES) over forested sites at realistically varying atmospheric stratification over a diurnal cycle to present an evaluation of the suitability of the Davenport coherence model over forested areas. The study aims to assist modelling efforts over forested areas by providing relevant comparisons and validation data.

2. Methodology and data

2.1. Measurements

Field measurements were taken from three tall masts in Sweden. The sites are Ryningsnäs (57.275 N,15.985 E), Hornamossen (57.981 N, 13.942 E) and Svartberget (64.256 N, 19.772 E). All sites have upstream forest cover in all directions consisting of managed forests (mixed patches of similar aged trees with clearings) covered mainly with coniferous trees. The forest height, h_c, within a radius of 100 m to the tower was determined 22 m for Ryningsnäs, 19 m for Hornamossen and 15.5 m for Svartberget, using ALS. All sites are representative of wind turbine sites with turbines installed nearby. Data was collected using 3D ultrasonics sampled at 20 Hz. The sonic data was processed as in [7] to provide statistics. In summary, the data was split into 30 minute segments and locally rotated to the direction of the mean wind, u defining the lateral mean wind $\overline{v} = 0$. Fluctuations, denoted with primes, were constructed by removing the mean, denoted with a bar. For velocity u, v, w and virtual temperature t. A stationarity criteria allowing for a maximum 10 % change in mean wind speed between adjacent 10 minute blocks and maximum 10 degrees of wind direction change between adjacent 30 minute blocks was applied to reduce the impact of synoptic and mesoscale transitions. Furthermore, a minimum wind speed of 3 m/s was required at 40 m height to filter out conditions non-relevant to wind power production. Directions impacted by wakes from wind turbines and/or the measurement tower was filtered out, as well as data affected by icing on the instruments. After these criteria were applied 28 % of the data remained in Ryningsnäs, 31 % in Hornamossen and 22 % in Svartberget. To determine the diabatic stability, the Obukhov length was calculated as

$$L = -\frac{u_*^3 \Theta}{\kappa g \overline{w't'}}, \tag{1}$$

where $u_* = (\overline{u'w'}^2 + \overline{v'w'}^2)^{1/4}$ is the friction velocity, Θ is the mean virtual temperature, $g = 9.81$ m/s is the acceleration due to gravity and $\kappa = 0.4$ the von Kármán constant. Data was sorted into the neutral category if $|L| > 500$ m.

Spectra were calculated as in [23], dividing the data into logarithmically spaced frequency bins and computing the cross spectral density ϕ for pairs of variables and positions. In order to reduce impacts from inertial effects, the spectra were furthermore filtered for mean wind speed at 100 m between 6-8 m/s. The simulations were processed in the same way as the measurements.

2.2. Simulations

The LES data was produced by the OpenFOAM model presented in [18], including the ability to explicitly model the forest drag and the heat transfer in the canopy leading to diurnal variations in the stratification of the flow. In order to include effects stemming from diurnal transitions, such as nocturnal low level jets, a strategy was adopted to run diurnal cycles where the net radiation varies in a as in observations [18]. To provide the LES with realistic forest density and topographical data, ALS was processed as described in [26]. Two sets of simulations were run, one with homogeneous forest cover (using the mean tree height and density from ALS) and one using the real heights and densities. Both simulations were run with a geostrophic wind speed of 12 m/s providing a mean wind at 100 m of approximately 7 m/s. For the simulations a domain of size $L_x \times L_y \times L_z = 7$ km $\times$ 23.5 km$\times$ $\sim$ 3.88 km was used. The domain had three refinements

with the innermost domain being of size $L'_x \times L'_y = 1$ km $\times$ 1.5 km with $\Delta_x = \Delta_y = 5$ m. The vertical resolution was $\Delta_z \approx 4$ m below 383 m after which a vertical stretching of 1.1 was applied. The SGS-model applied was the revised Deardorff model of Moeng [27] which use the geometric average of the grid cell size as a length scale unless the stratification is strong enough, in which case the length scale is proportional to the product of the turbulence velocity scale and the Brunt-Vaisala frequency. In the cells where forest is present the dissipation is furthermore enhanced. For full details regarding the simulations, please see [18].

2.3. Evaluation measures

The turbulence characteristics, such as the ratio between standard deviations, σ_{u_i} longitudinally, laterally and vertically, as well as length scales are evaluated with the power spectrum of each velocity component, $|\phi(u_i, z)|^2$ where u_i can be either the longitudinal, u, lateral, v or vertical w velocity component and z is the height above ground.

In order to display the variation of the statistics with stratification we have opted for a simple division into daytime and nighttime data, in addition to neutral conditions (reflecting that much of the wind energy standard models rely on the assumption of neutral conditions) and a category for the average of all of the data. The idea being that a quantitatively appealing measure for the stratification such as h_c/L inevitable leads to a discussion of which weight a certain stability class should have when representing averaged conditions. Here, the definition of night, local time between 22:00 and 04:00 and day, local time between 10:00 and 16:00 each represent the same share of all the data for every site (1/4 of the time for each with a transition period of 6 hours in between). Figure 1 shows the distribution of h_c/L for all of the sites as well as the median for the subcategories, *day*, *night*, *neutral* and *all data*. As the data shows, daytime conditions represent moderately unstable stratification and nighttime conditions represent stable conditions. An important remark is that *all data* is biased towards stable stratification, reflecting the fact that the mean atmosphere is stably stratified. Even the neutral class is slightly biased towards stable conditions for this reason, but to a smaller degree. Part of the reason that the median stratification daytime conditions is close to neutral is that wind speeds at 40 m lower than 3 m/s was filtered out which had the side effect of removing the very unstable conditions.

To evaluate the effect of turbulence on larger sections of the rotor, the coherence

$$\mathrm{Coh}(u, x_i, u, x_j) = \left(\frac{|\phi(u, x_i, u, z_j)|^2}{\phi(u, x_i, u, x_i)\phi(u, x_j, u, x_j)} \right)^{1/2}, \tag{2}$$

where x_i refers to vertical or lateral separation of the two points, was calculated for both the measurements and simulations. The values were then compared with IEC standard models for both power spectra and coherence to investigate if the standard model applies over forests.

In addition to an evaluation of the spectral character of turbulence, mean profiles of relevant quantities were constructed, similar to [6] and [7]. The data was split into the above categories and the confidence level, calculated as 1.96 times the standard error of the mean was determined. The confidence level is shown only for the all data category in order to reduce cluttering in the figures.

3. Results

The section begins with first order statistics and turbulence intensity (Figure 1) followed by profiles of higher order statistics (Figure 2) and concludes with spectral statistics (Figure 3).

3.1. Mean profiles and turbulence intensity

The mean wind profile, shown in Figure 1 (b), linear height and (d) logarithmic height, follow the same qualitative behaviour in all three sites, with a logarithmic shape of increasing curvature in

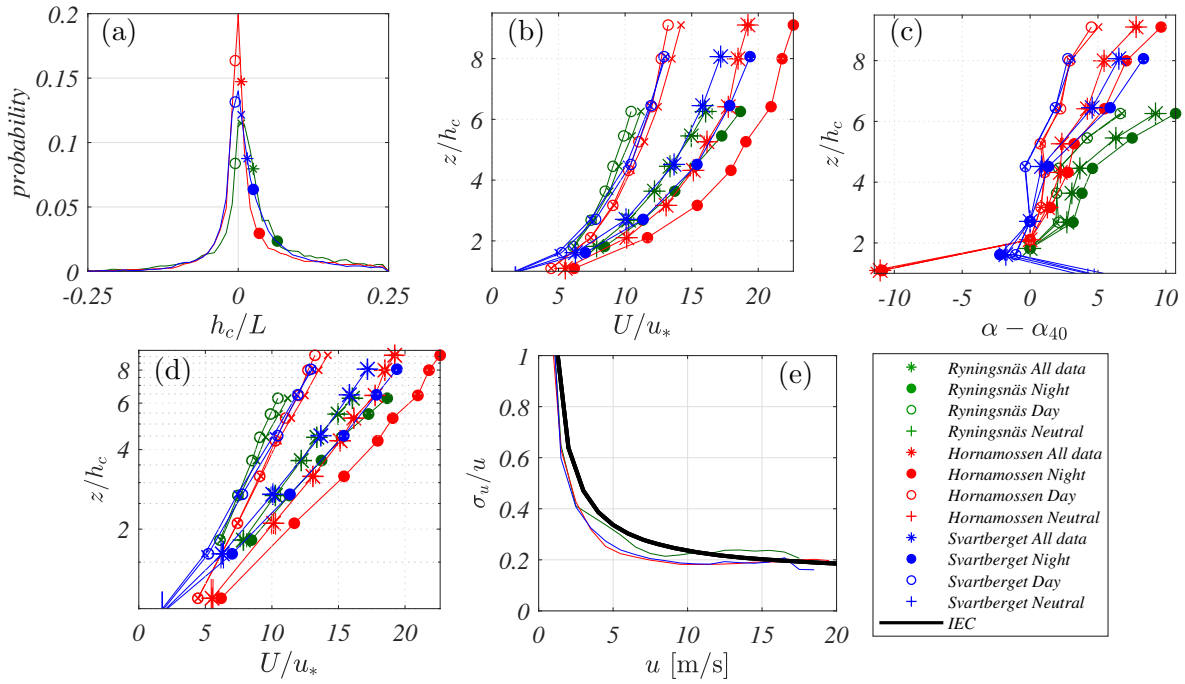

Figure 1. Distribution of the diabatic stability (a), average profiles of mean wind speed (b) and (d), wind direction (c) and the 90:th percentile of turbulence intensity as function of the mean wind speed (e) for the measurements and IEC standard turbulence class 3 A+. Markers in (a) represent the median in the categories *day*, *night*, *neutral* and *all data* according to the legend (f).

unstable conditions and decreasing curvature in stable conditions. The roughness length is the highest for Ryningsnäs and the lowest for Hornamossen, but the values are similar. As expected from the non-symmetrical shape of the stability function for the non dimensional wind gradient [28], the neutral conditions are more similar to unstable (day) than stable (night) conditions.

Judging from Figure 1 (c) all of the profiles are veering above the forest. Typical values appear to be a few degrees of turning over 100 m in daytime conditions and a mean turning of close to 10 degrees per 100 m in night conditions, again with the mean of all data being closer to that of nighttime.

In the IEC standard levels for the 90:th percentile of turbulence intensity is given as a function of the mean wind speed and a reference intensity that determines the class of the turbine. The IEC curve for class 3 A+ turbines is reported in Figure 1 with the 90:th percentile of turbulence intensity from the measurements. As the values in the figure are the 90:th percentile of the turbulence intensity they do not reflect the average turbulence intensities, which are instead reported in Figure 2 (a). Again it is clear that Ryningsnäs has a higher roughness whereas the curves of Hornamossen and Svartberget follow each other. There is more curvature in the measured curves than the IEC standard for 90:th percentile turbulence intensity, leading to an overestimation by the IEC standard for wind speeds in the most common range.

3.2. Higher order statistics

A selection of higher order statistics relevant to site assessment and wind turbine design and/or selection is presented in Figure 2. As expected, the high turbulence intensity reflects the rough surface. All three sites follow similar shapes, with turbulence intensity decreasing with height (mainly due to the increase of the wind speed). The turbulence intensity is considerably lower at

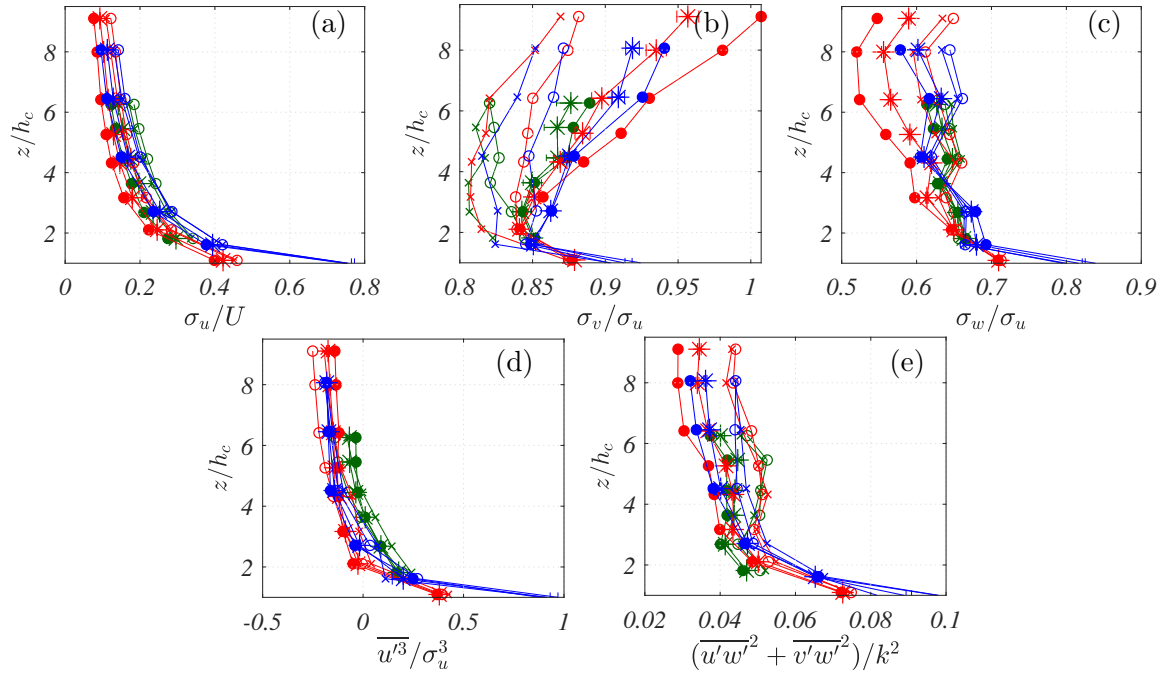

Figure 2. Turbulence intensity (a), lateral anisotropy (b), vertical anisotropy (c), skewness of the wind speed (d) and the square of the ratio between shear stress and turbulence kinetic energy (e). Markers and colours are as in Figure 1

night than at day. The ratio between nighttime values to daytime values decrease with height, with night values roughly 60-75 % of daytime values at 100 m height.

The IEC standard stipulates that for load calculations σ_v should exceed 70 % of σ_u and σ_w should exceed 50 % of σ_u. In the measurements both ratios vary with stratification, particularly σ_v/σ_u. The directional shear of the wind profile influence the ratio of σ_v/σ_u, with higher values reached at higher elevations. Neutral conditions stand out as giving the lowest values of σ_v/σ_u. There is also a clear trend that more energy moves to the horizontal components in nighttime conditions with all sites displaying lower values of σ_w/σ_u during night.

The skewness of the velocity profile follow a typical pattern with positive values close to the forest edge [6, 29] and slightly negative values at higher elevations. Over the typical swept area, which normally starts around 2 h_c, negative values dominate for all sites, indicating that slow ejections are stronger than fast sweeps. The effect of stratification is less evident on the skewness, but a common feature is that the negative values at higher elevation is more pronounced during day, possibly indicating an impact of convective plumes.

In order to provide input for RANS modelling over forests, the square of the ratio of shear stress to turbulence kinetic energy is reported in Figure 2 (e). The reason is that for regions where turbulence energy production and dissipation are equal, this measure approaches the desired value of the C_μ constant in the $k-\epsilon$ closure for RANS models. As reported by [30, 6] production approximately equals dissipation above $z/h_c = \approx 3$. Judging from Figure 2 (e), the value is similar for all sites and only weakly changes with height. Day time values are 20-50 % higher than nighttime values. The mean of all data is close to 0.04 for all sites at heights similar to a modern wind turbine hub height ($z/h_c \approx$5-8).

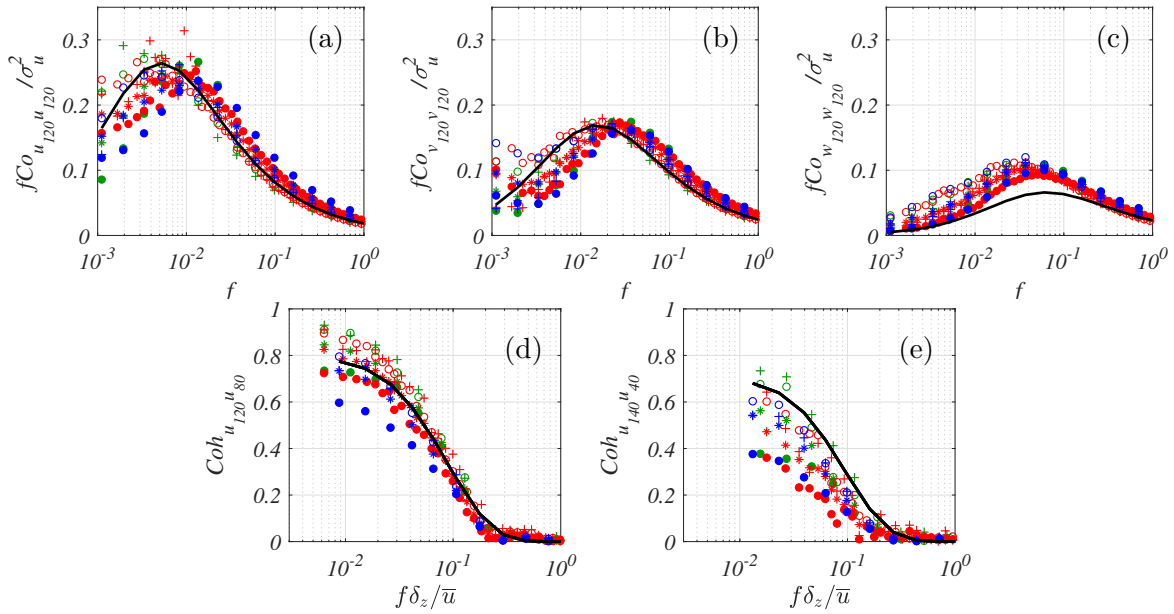

Figure 3. Power spectrum of u, v and w (a)-(c) and u-coherence with a vertical separation between 80 and 120 m (d) and 40 and 140 m (d). The full black line represents the IEC standard.

3.3. Spectral statistics

The comparison of power spectra (Figure 3 a, b and c) reveal that when scaled with the streamwise variance, the main difference between different stratification lies in the peak frequency of the spectrum, as expected. For all measurement sites, the neutral class is closer to the daytime class and the average of all of the data is closer to the nighttime class, reflecting the larger effect on turbulence by stable stratification than that of unstable stratification. Data from the two southernmost sites collapse well, but the northern site, Svartberget, displays shorter turbulence length scales at the same height, likely an effect of the lower forest height there, possibly in combination with the surrounding topography. The IEC standard spectra fits the measurements well in neutral conditions for u and v, but underestimate the magnitude of w and peaks at a shorter length scale compared to the observations. At all sites the familiar pattern of decreased spectral density for low frequencies in stable conditions (see for instance [19]) appear clearly during nights even though the curves are normalised by the variance and not the spectral density in the inertial subrange.

To model the spatial extent of the turbulence eddies, IEC recommends either the model from Mann [21] or a model based on Davenport [20] which only requires mean wind, separation distance and a length scale that is given by the elevation. Coherence for approximately 40 m separation as well as approximately 100 m separation is presented in Figure 3 (d) and (e) respectively. From the figure it is clear that for large separations the IEC Davenport model is mostly overestimating coherence relative to the measurements, whereas it agrees better with the data for the smaller separation distance. Also coherence follow the pattern displayed by the other statistics where night conditions stand out relative to the neutral conditions. Especially for the larger separation distance it is clear that the smaller length scale of turbulence is limiting the coherence to values well below those predicted by the standard in agreement with other reports of coherence over forested areas in stable stratification [9].

To facilitate a comparison of the IEC model for lateral separations LES have been used. Coherence estimates from the simulations indicate that lateral and vertical separations behave much in the same way, and that the Davenport coherence model predicts the observed shape

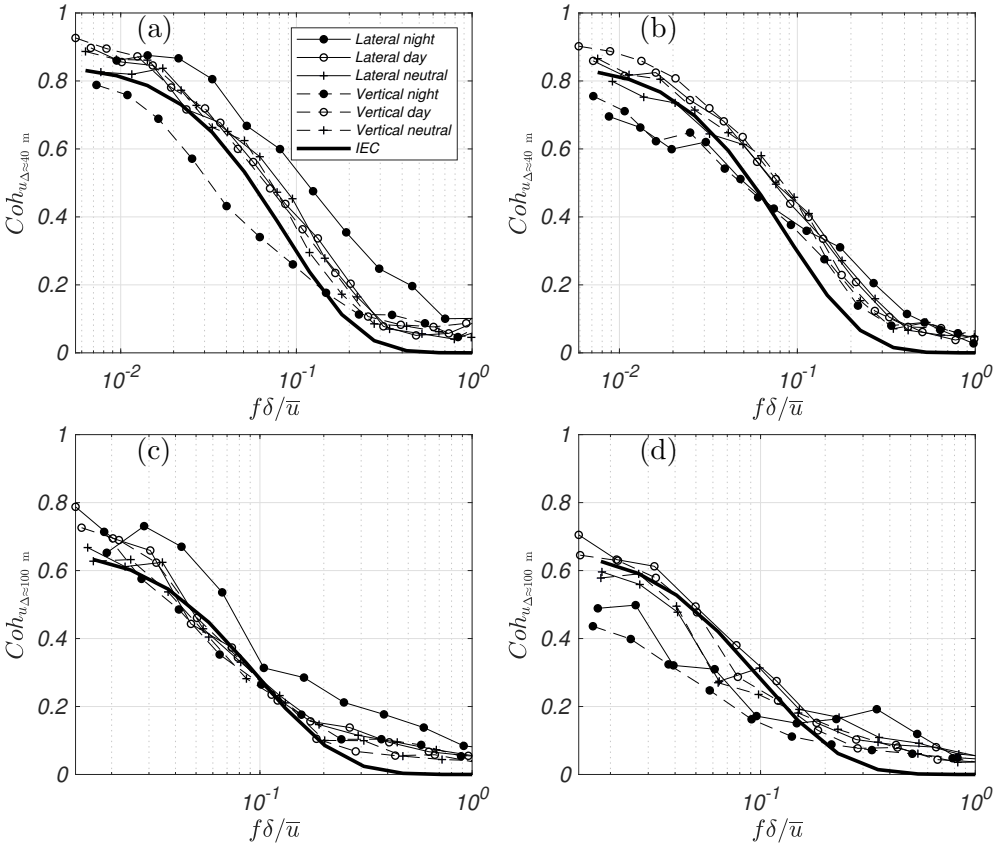

Figure 4. Lateral (full lines) and vertical (dashed lines) coherence of u from LES over homogeneous forest (a) and (c) and heterogeneous forest (b) and (d). In (a) and (b) the separation distance is 40 m while in (c) and (d) the separation distance is 100 m. The thick black line is the IEC standard coherence, same as in Figure 3 (d) and (e)

fairly well. Figure 4 depicts lateral as well as vertical coherence for two different separation distances, 40 and 100 m. In the left panel, the results come from a simulation using a homogeneous forest cover, while the right ones come from a simulation using measured, heterogeneous forest cover. The LES also shows the same tendency for nighttime coherence to be less than daytime coherence in the heterogeneous forest cover simulation, but in the homogeneous simulation the lateral nighttime coherence is instead greater than the daytime equivalent. Other than nighttime conditions the curves collapse with limited scatter.

4. Discussion

All three investigated sites are within managed forests which means that the forest cover is patchy and heterogeneous. Despite that, the statistics follow very similar behaviour. Some part of this may be attributed to the averaging over several wind directions. Results from [12] and [10] point to that with heterogeneous forest cover, wind statistics could at least weakly be a function of direction. But overall, the similarity between the results from the three sites indicate that the statistics are representative of forested conditions over mildly varying topography.

A common feature for all the investigated measures is the difference between day and night. While most of that effect arguably stems from different stratification, some effects could also be coupled to dynamics related to the transition between different stability regimes, for instance the ratios of standard deviations among the velocity components. Future studies could potentially

make use of other categories, such as traditional stability measures as in [7] or as function of the solar elevation angle as in [31] in combination with relative occurrences of transitional features such as low level jets, multi-layer structured boundary layers or intermittent turbulence.

Particular focus on flow dynamics specifically related to the presence of forests is a point for further investigation. The present division of data does not reveal any strong impact from flow regimes such as intermittency cycles, as evident by the relatively similar skewness over all categories, or canopy waves although some of the spread in σ_v/σ_u and σ_w/σ_u could potentially be explained by that [6].

It is clear from several earlier studies, both from observations [3, 4] and modelling [1, 11, 10] that forest conditions represent challenges in terms of loads on wind turbines, but the specific reason for this remains unclear, whether it is mainly related to the generally larger turbulence magnitude or the character of turbulence itself. As presented in this work, statistical models for turbine design agrees reasonably well with observations, especially in neutral conditions. It is a possibility though, that the large magnitude of turbulence together with misrepresentations of turbulence size estimates leads to suboptimal control strategies from a load perspective. Future investigations into control strategies specifically aimed at winds over forests could potentially answer that question.

With regards to power spectral densities, Figure 3 point to clear differences between the turbulence character in day and night. The behaviour is consistent over all the investigated sites to there is reason to assume it is a general feature. It is likely the impact of stable stratification that leads to the overestimation of the turbulence scale (as measured by the peak of the power spectra). The fact that z/L normally increase with height [7] together with the correctly predicted spectral peaks in neutral conditions points to this. There could also be some impact of the displacement height, which is not accounted for in the calculation of the length scale.

Despite being developed for very different conditions, the IEC Davenport model for coherence fits the data fairly well. There is a persistent overestimation for large separations, primarily driven by stable stratification, a pattern that is present in both the observations and the LES over heterogeneous vegetation. A reduction of the length scale used in the model for stable stratification could potentially increase the accuracy and provide better statistics for load calculations. On the other hand, the comparison is limited to the simpler of the two recommended spectral models in the IEC 61400 standard and a comparison with the Mann model [21] as well as its extension to non-neutral stratification [23, 24] would be interesting. While the results in Section 3.1 and 3.2 compare well with standard surface layer statistics, it is evident that as turbine rotor size increase, it will become important to include the effect of limited length scale growth with height, nonlinear shear and changing wind direction over the rotor also on the spectral statistics used to create synthetic turbulence for load calculations. Current state of the art LES, including stratification, Coriolis effect and explicit drag modelling could also become a very interesting alternative for load calculation for truly site specific assessment, provided that computational efficiency could be improved. A question that then needs further attention is the relative importance of domain size and resolution. Whether the conclusion that coarse LES can provide accurate larger scale turbulence [32] carries over to load calculations is a point for future investigations.

5. Conclusions

The study has presented a set of statistics relevant for wind energy over forested areas. All the presented results clearly point to the contrasting nature of daytime and nighttime conditions and its influence on turbulence statistics. For the majority of the investigated variables, the average of all data falls closer to nighttime (stable stratification) than daytime (unstable stratification) or neutral conditions. This points to the importance of including stable conditions when modelling

wind and turbulence in the atmospheric boundary layer. There are no strong indications in the data that the impact of forest cover directly alters the turbulence statistics in a significant way for heights relevant to wind energy. There might however be important indirect effects that are coupled to the evolution and amplitude of the diurnal cycle of stratification.

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