Response to the comments by anonymous referee #2 on manuscript WES-2026-100

Turbulence characterization in near-coastal environment using triple short-range lidars and mast anemometry

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Note: Line numbers cited by the referee refer to the WESD preprint, whereas line numbers cited in the response refer to the revised manuscript.

1. General comment

Referee comment

Overall, the article provides a unique analysis of a rich dataset containing sonic, cup anemometers, and a triple short-range lidar system. It's an excellent contribution to the wind energy community. The article is scientifically sound, easy to follow and comprehensive.

I believe the article is suitable for publication in WES after some minor additions/revisions. Following are some of my observations/comments which can improve the present quality of the article even further:

We thank the reviewer and appreciate the positive feedback and constructive comments on our manuscript. We have addressed the individual comments below and updated the manuscript accordingly.

2. Specific comments

Referee comment

Line 164. Please report what fraction of samples were excluded by the "stability-classes" criterion. It would also be interesting to show and compare $\zeta(25m)$, $\zeta(55m)$, and $\zeta(110m)$ statistics. Estimate the mismatch between the stability classes at these heights and discuss how this mismatch could affect the vertical coherence results, especially for the largest separations.

We agree that the fraction of samples excluded by the atmospheric stability criterion is valuable information. We have therefore included the number of remaining samples in Table 1 and expanded the corresponding sections of the manuscript as detailed below.

In addition, we have added Appendix C, which presents the distributions of the stability parameter ζ at the 55 m and 25 m measurement levels. While the distributions exhibit similar trends with respect to mean wind speed, wind direction, month, and time of day, the fraction of near-neutral conditions increases with decreasing height. As discussed in the methodology section (line 171), the potential influence of this mismatch on the vertical coherence analysis is reduced by excluding samples for which the stability estimates at different heights differ substantially.

Changes to manuscript

Added a row to Table 1, specifying the number of samples after the stability filter.

Updated the values in Fig. 5 and in the last row of Table 1.

Line 66:
In the present work, nearly 500 h of lidar measurements acquired over a five-month period are analyzed [...]

Line 140:
Finally, the datasets are filtered to include only atmospheric stability conditions satisfying $|\zeta| \leq 2$. The estimation of the non-dimensional stability parameter ζ is described in Sect. 3.2.

Line 143:
Prior to applying the atmospheric stability filter, approximately 57 % to 63 % of the sonic anemometer data remain available. Restricting the dataset to $|\zeta| \leq 2$ reduces the availability to 40.0 %, 55.5 %, and 61.5 % for the upper, intermediate, and lower measurement levels, respectively. The reduced availability at higher elevations is primarily due to the more frequent occurrence of stability conditions outside the selected range. Closer to the surface, enhanced mechanically generated turbulence contributes to the higher occurrence of near-neutral conditions, resulting in a larger fraction of data satisfying the stability criterion.
For the cup anemometers, the availability is slightly higher (53.6 % to 65.5 %), [...]

Line 152:
For the SRWS measurements, the final data availability is the lowest (39.1 %), [...]

Line 276:
The corresponding distributions at $z = 55$ m and $z = 25$ m are provided in App. C.

Added App. C.

Referee comment

One of the reasons mentioned by the authors to perform this analysis is to characterize wind turbulence for modern multi-megawatt wind turbines. A modified coherence model is also fitted to the measured vertical and lateral coherence values at multiple separations, including some beyond 100 m. However, there is substantial uncertainty in the coherence measurements for dz ≥ 90 m and dy ≥ 90 m, which are important separation distances for large wind turbines. Generating synthetic wind fields from this data may yield unrealistic results.
Including confidence intervals or uncertainty quantification alongside the fitted model values in the tables in Appendix C can be valuable.

We thank the reviewer for this comment. We acknowledge that coherence estimates at the largest separations are associated with increased uncertainty due to the limited number of available samples. Following similar comments from Reviewers 1 and 3, we have removed estimates for which the sample size was considered insufficient, thereby improving the robustness of the presented results. For the remaining separations exceeding 90 m, the estimates remain consistent with the overall coherence trends across separation distance and were therefore retained.

With regard to the fitted model parameters, we agree that an uncertainty quantification would be valuable. However, deriving statistically meaningful confidence intervals is not straightforward in the present analysis because the empirical coherence model is fitted to ensemble-averaged coherence estimates within each stability class rather than to independent realizations. Consequently, the uncertainty associated with the fitted coefficients cannot readily be inferred from the available data and we have therefore not included confidence intervals in App. A and B. Instead, we would like to refer to our response to Reviewer 3 regarding the range of normalized separations $d\,z^{-1}$ over which the fitted coherence model is intended to be applied.

Referee comment

Line 401. I am not totally satisfied with the reasoning given for the disparity between $\gamma_{w,\mathrm{sonic}}$ and $\gamma_{w,\mathrm{lidar}}$ in Figure 16. Furthermore, the authors dismiss the possibility that this could be due to lidar volume-averaging effects. Please provide more sound, quantitative reasoning for this mismatch.

We agree that the discussion of the discrepancy between the sonic- and lidar-based estimates of γ_w^z can be strengthened. As discussed in the manuscript, we do not consider the attenuation of the lidar spectra to be the primary cause of the reduced coherence. The attenuation is expected to largely cancel when the coherence is calculated as the normalized cross-spectrum. Furthermore, the discrepancy persists at low wavenumbers, where the spectral attenuation is negligible.

A more plausible explanation is that the retrieval of the vertical velocity and the subsequent coherence estimation from the SRWS measurements introduce additional decorrelation effects that are specific to the w component. We have incorporated these potential effects into the revised discussion below.

Changes to manuscript

Line 434:

As reported by Cheynet et al. (2016a), a reduction of the lidar-based coherence estimates due to spectral attenuation related to volume-averaging is unlikely because the cross-spectra are normalized by the correspondingly attenuated auto-spectra. [...]

The velocity reconstruction and coherence estimation based on the SRWS scans may, however, introduce additional decorrelation effects that are specific to the w component. Due to its greater spatial variability within the finite measurement volumes, the vertical velocity is more sensitive than the horizontal components to departures from the assumptions underlying the velocity reconstruction. Furthermore, the correction for the time lag between the vertically separated extraction points relies on Taylor's hypothesis of

Changes to manuscript (continued)

frozen turbulence and is thus expected to be less accurate for the vertical velocity component because of the more rapid temporal evolution of vertical motions. Both effects may contribute to reducing the correlation between the SRWS-derived vertical velocity time series at different heights.

Referee comment

Since the test site is coastal and offshore winds are dominant, some or all of the measurements must be within the internal or transitional boundary layer. The authors have not discussed any impact of the development of the internal boundary layer on the turbulence statistics measured at the site. Please discuss how this affects the turbulence statistics, especially the vertical coherence values. Can the large uncertainty in measured coherences at large separations be explained by the development of an internal boundary layer? Specifically, how does the transition from the marine boundary layer to the inland site modify the integral length scales and the vertical coherence decay coefficients compared to pure offshore sites like FINO1?

These are important considerations and partly overlap with a comment raised by Reviewer 1. Given the distance of approximately 2 km between the site and the coastline, the measurements are expected to be within the internal boundary layer (IBL) for all wind directions originating from the sea. Following the suggestions of Reviewer 1, we have removed the terms "offshore flow" and "offshore sector" from the manuscript, as even the northwestern sector cannot be regarded as representative of undisturbed offshore conditions.

To further address the potential influence of the IBL, we have added Fig. 15, which compares the neutral auto-spectra for four wind direction sectors characterized by different upstream terrain. The western and northwestern sectors exhibit increased low-frequency energy compared with the inland sectors, consistent with the increase in integral length scales shown in Fig. 10. However, these directional differences are limited, suggesting that the flow has already undergone substantial change within the IBL. Consequently, the integral length scales and coherence remain lower than those reported by Cheynet et al. (2018) for the FINO1 site.

The increased uncertainty in the coherence estimates at large vertical separations is, however, more likely to be a result of the limited number of available samples at these separations, rather than being caused by the IBL, as it persists even when excluding data from northwestern direction.

3. Minor comment

Referee comment

Figure 3 (b). I am assuming the coordinates should be N pointing up and E pointing right, rather than W. Please correct them.

We thank the reviewer for this observation. This was indeed a typographical error, and we have corrected the figure in the revised manuscript.

References

Cheynet, E., Jakobsen, J. B., Snæbjörnsson, J., Mikkelsen, T., Sjöholm, M., Mann, J., Hansen, P., Angelou, N., and Svardal, B.: Application of short-range dual-Doppler lidars to evaluate the coherence of turbulence, Exp. Fluids, 57, 184, https://doi.org/10.1007/s00348-016-2275-9, 2016a.

Cheynet, E., Jakobsen, J. B., and Reuder, J.: Velocity Spectra and Coherence Estimates in the Marine Atmospheric Boundary Layer, Bound. Layer Meteorol., 169, 429–460, https://doi.org/10.1007/s10546-018-0382-2, 2018.