Response to the comments by anonymous referee #3 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

The authors obtained wind velocity measurements over a large period and by multiple instruments. Of particular interest, is the bowtie-shaped lidar-based velocity measurements. They allow analysis of the three components of the wind over vertical and lateral separations, which is uncommon. The authors explore single- and two-point statistics and introduce a coherence formulation that includes extra terms to account for well-known limitation of the simple Kaimal spectrum with Davenport's exponential.
The authors do a great job at showing the spectra and coherence estimates of the different instrument and discuss the relevant differences. Overall the manuscript is an important contribution that will hopefully be used as basis for other coherence-related work.
Find some comments below.

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

2. Specific comments

Referee comment

1. The manuscript needs additional clarification in terms of notation used for integral scales. For example, one can use the notation L_w^z to mean the vertical integral length scale, which characterizes how w is correlated over vertical separations. Or, the notation L_w^x, a measure of the w fluctuations along the mean wind direction. This distinction is especially relevant as the authors use frozen turbulence to convert between L_i and T_i using the mean horizontal wind speed. Using Eq 16 as is means one is obtaining the streamwise integral length scale of w, or, L_w^x. I make this comment fully understanding the IEC standards do not make this distinction but I believe the manuscript could benefit from additional clarity.

We thank the reviewer for this comment. We agree that it is important to distinguish between streamwise, lateral, and vertical integral length scales. In the present work, all integral length scales are derived from single-point time series using Taylor's hypothesis of frozen turbulence and therefore represent streamwise integral length scales. As no lateral or vertical integral length scales are considered, we prefer to retain the simpler notation L_i for improved readability. To avoid any ambiguity, we have added an explanatory sentence around Eq. (16) explicitly stating that L_i refers to the streamwise integral length scale throughout the manuscript.

Changes to manuscript

Line 222:
Under the assumption of frozen turbulence, the streamwise integral length scale can be estimated from a single-point velocity time series as [...]

Line 228:
Throughout this work, L_i denotes the streamwise integral length scale of velocity component i.

Referee comment

2. Also on notation, the coherence could use additional symbols to indicate the direction. For example, Figs 15-17 show vertical co-coherence and Fig 19 shows lateral co-coherence, but they all use the same symbol γ_i, with $i = u, v, w$.

We agree that the notation of the coherence needs clarification regarding the direction of separation. As we are showing both vertical and lateral coherence, we have updated the manuscript introducing the notation γ_{ij}, with $j = \{x, y, z\}$ denoting the separation direction.

Changes to manuscript

Line 194:
In this study, unless stated otherwise, *coherence* refers specifically to the co-coherence γ_{ij}, i.e., the real part of the complex coherence [...] with f denoting the frequency in Hz and $j = \{x, y, z\}$ the separation direction.

Updated notation in Eqs. (20) – (22), (25), and (B1).

Updated axis label in Figs. (16) – (18) and (21).

Referee comment

3. **Figure 9** shows how sensitive the computation of integral length scales L_i^z is to the method chosen. Despite that, the authors continue their analysis using one of those methods – auto-correlation function – without further justification. It is unclear if Figure 10 (for example) and supporting conclusions would remain the same if a different method were to be used.

Figure 9 compares the integral length scales derived from the auto-correlation functions with those obtained from the IEC standard and from fitting the Kaimal spectrum to the measured auto-spectra. Both the IEC standard and the Kaimal spectral model are only applicable to neutral atmospheric conditions and therefore do not provide a basis for estimating length scales consistently across different stability regimes, as required for the subsequent analysis. In contrast, the auto-correlation approach can be applied independently of atmospheric stability, which is why we retain this method only.

Referee comment

4. **Fig 10(a)** shows the integral scales generally increaseing as ζ approaches zero from a negative number– going from a strongly unstable scenario to a weakly unstable towards neutral. That is opposite of what I was expecting, as the more boyancy in the flow, the higher the turbulence production and the larger the integral scales. The authors should mention and offer explanations as to why that was the case. (Is this an artifact of the auto-correlation method chosen?)

We thank the reviewer for this comment and agree that this observation is not intuitive. As discussed in our response to Reviewer 1, we suspect that this behavior may reflect limitations of Taylor's hypothesis of frozen turbulence under strongly unstable conditions. We have expanded the discussion in the revised manuscript to address this potential effect and to clarify that the observed reduction is not necessarily to be interpreted as evidence of smaller turbulent structures.

Changes to manuscript

Line 308:
The dependence of the integral length scales on atmospheric stability and wind direction is illustrated in Fig. 10. Under neutral conditions, the integral length scales are within the ranges of 100 to 250 m for L_u, 30 to 100 m for L_v, and 10 to 50 m for L_w. From neutral to weakly unstable conditions, the length scales increase, consistent with enhanced turbulence generation due to buoyancy. Unexpectedly, this trend does to not persist in the strongly convective regime, which may be related to limitations of Taylor's hypothesis of frozen turbulence. The estimation of integral length scales from single-point temporal auto-correlation functions assumes that turbulent structures are advected past the measurement location without undergoing significant evolution. Under unstable stratification, buoyancy-driven turbulence may accelerate the temporal evolution of turbulent eddies, causing the measured auto-correlation functions to decay more rapidly. Consequently, the slightly smaller integral length scales estimated under strongly unstable conditions may not necessarily reflect smaller turbulent structures, but rather indicate departures from Taylor's hypothesis of frozen turbulence.
From neutral to weakly stable conditions, all length scales decrease substantially as buoyancy transitions from enhancing to suppressing turbulence.

Referee comment

5. **Fig 10(b):** values of L_v are about the same order of magnitude as the values for L_u. Does that hold true for L_u^x and L_v^y? Seems like the SRWS dataset can help answer this question.

We agree that the SRWS measurements could in principle be used to estimate integral length scales from lateral and vertical separations. However, in this work we characterize the correlation across these separations in terms of spectral coherence rather than integral length scales. This approach allows the scale-dependent correlation to be assessed across different frequencies and is also directly relevant to the parameterization of coherence for synthetic wind field generation, which is one of the intended applications of the results.

The streamwise integral length scales presented in this study serve primarily to characterize the extent and deformation of turbulent structures and their dependence on atmospheric stability. The ratio of the streamwise integral length scales of the cross-wind and the along-wind turbulence, L_v/L_u, is around 0.75 to 1 under unstable conditions, and decreases to 0.25 to 0.5 in neutral and stable atmopshere, which appear to be reasonable ranges.

Referee comment

6. **Line 278:** providing vertical profiles obtained with the SRWS scan is not "validation". Using terms like "further validation" also implies the author mean that some sort of validation is provided by recovering typical and expected seasonal and diurnal patterns on the data. As accurately described, recovering these patterns indeed "support[s] the reliability of the stability classification", but does not provide any validation.

We agree that the term "validation" was not appropriate in this context, as the mean wind profiles can only provide supporting evidence for the reliability of the stability classification. Moreover, following the suggestion of Reviewer 1, we have removed the appendix containing the mean wind profiles, as it does not contribute directly to the turbulence analysis and the stability classification based on Monin–Obukhov length estimates from sonic anemometer measurements is a well-established approach.

Referee comment

7. **Fig 15:** Just a suggestion: I understand dz for the sonics and cups completely define the points per earlier description, but it would be nice to also have the z value right on the caption here, similar to Fig 16.

We appreciate this suggestion and have added the average measurement heights to the legend.

Changes to manuscript

Updated Fig. 16.

Referee comment

8. **Line 408:** an "increasing stability" is not a well defined term. Consider using "as ζ increases…". This comment applies to every instance of "increasing stability".

We agree with the reviewer and have replaced the term throughout the manuscript.

Changes to manuscript

Line 448:
From unstable to stable conditions, coherence decreases, reflecting the reduction in turbulent length scales.

Line 474:
The reduction of turbulent length scales from unstable to stable conditions is reflected in the lateral coherence.

Referee comment

9. **Fig 17:** why does the scatter get worse as separation distance increase? I understand that N is lower, but is that enough to justify increased scatter? Also- similarly to my comment above, would be helpful to know here if z is the same for all these measurements (may be worth stating that in the figure caption).

We thank the reviewer for these comments. Coherence estimates are subject to statistical uncertainty and inherently very noisy. The smoothness observed at smaller separations results from ensemble averaging over a relatively large number of samples. As the separation increases, the number of available realizations reduces substantially, leading to increased scatter.

We agree that the measurement height should be specified when comparing coherence estimates at different separation distances. In the original analysis, the estimates shown in Fig. 18 were obtained by averaging across all heights sampled by the bow-tie scan. As noted in the reviewer's subsequent Comment (#11), this is an oversimplification because coherence may vary substantially with height. We have therefore revised the analysis presented in Figs. 18 and 21 by restricting the ensemble averaging to estimates obtained at comparable heights. The chosen height ranges have also been added to the figure captions.
In addition, following Comment #11, we have added Figs. 19 and 22, which show the vertical and lateral coherence as a function of measurement height for a given separation distance. These figures provide further insight on the dependence of the coherence estimates on height.

Changes to manuscript

Updated Fig. 18 and 21.

Figure 18. Vertical co-coherence of (a) – (e) along-wind, (f) – (j) cross-wind, and (k) – (o) vertical velocity from SRWS for separations ranging from 10 m to 160 m under strongly unstable (left) to strongly stable (right) conditions and average heights of $110 \text{ m} \leq z \leq 140 \text{ m}$.

Changes to manuscript (continued)

Line 453:

To obtain meaningful averages as a function of stability and separation distance, the ensembles are restricted to estimates obtained at comparable measurement heights of 110 m ≤ z ≤ 140 m.

Figure 21. Lateral co-coherence of (a) – (e) along-wind, (f) – (j) cross-wind, and (k) – (o) vertical velocity from SRWS for separations ranging from 10 m to 160 m under strongly unstable (left) to strongly stable (right) conditions and a measurement height of 125 m.

Line 481:

To obtain meaningful ensemble averages, the lateral coherence estimates shown in Fig. 21 are restricted to a measurement height of 125 m, corresponding to estimates obtained along the horizontal segment of the bow-tie pattern.

Referee comment

10. **Fig 17:** panel (o) looks like the 160 m curve fit has $\gamma_w = 1$ somehow being enforced at $k = 0$. Please check that curve fit. Seems unlikely that the single point at around $\gamma_w = 0.42$ would affect the fit that much (or at least it shouldn't). Overall some fits for 160 m are departures from the trend for other separations. I know the sample size is much smaller– if the differences can all be attributed to N, then the authors should consider dropping 160m altogether from the coherence analysis. One could argue it does not provide enough data for reliable estimates.

We agree that some of the curve fits in Fig. 18 are strongly influenced by substantial scatter in the coherence estimates and do not consistently follow the trends observed at smaller separations. As discussed in our response to the previous comment, we attribute this increased scatter primarily to the reduced number of available samples at the largest separations.
While there is no artificial constraint forcing $\gamma_w = 1$, the fit to the limited and highly scattered data produces an unreliable coherence estimate. Following the suggestions of Reviewers 1 and 3, we have therefore removed the 160 m separations for $|\zeta| > 0.6$.

Changes to manuscript

Updated Fig. 18.

Figure 18. Vertical co-coherence of (a) – (e) along-wind, (f) – (j) cross-wind, and (k) – (o) vertical velocity from SRWS for separations ranging from 10 m to 160 m under strongly unstable (left) to strongly stable (right) conditions and average heights of 110 m ≤ z ≤ 140 m. The 160 m separation is omitted for $|\zeta| > 0.6$ due to high uncertainty associated with a limited sample size.

Referee comment

11. **Line 418:** The fact that pair of points located at (e.g.) z=55,75 and z=195,215 can be averaged together requires some additional jusitifications. As I was reading through, I noticed Fig 17 could benefit from having the z value as well, but this sentence explains why this is not the case. How does the coherence of same dz but varying z compare?
I understand Fig 19 tackles part of this question. Fig 19, however, shows several points where the Eq 24 isn't a good fit. Do the points that don't follow the fit have a common pattern/trend to them in terms of location?
It's hard to look at Fig 19 and conclude that these pair of points can be averaged over. I think the question of how the vertical coherence for the same separation changes over different mean heights is an important one and this dataset can help answer. Having this discussion would not only enrich the manuscript but also provide (or not provide) the needed evidence for the assumption given on line 418.

We agree that averaging coherence estimates with the same separation distance across substantially different measurement heights is an oversimplification, and that the height dependence should be explicitly examined. As described in our response to Comment #9, we have therefore revised the analysis and restricted the range of measurement heights when ensemble-averaging the coherence estimates presented in Figs. 18 and 21.
To further investigate the dependence of coherence on measurement height, we have added Figs. 19 and 22, which show the vertical and lateral coherence estimates, respectively, for a fixed separation distance as a function of the average measurement height.
We further agree that the deviations from Eq. (24) in Fig. 20 require further discussion on the validity range of the coherence model. We have elaborated on this in our response to Comment #12.

Changes to manuscript

Added Fig. 19

Line 457:
Additionally, coherence is affected by the measurement height, which is not accounted for by the Davenport model. The height dependence of the vertical coherence is examined in Fig. 19 for a fixed separation distance of $d_z = 160\ \mathrm{m}$ and neutral conditions. A reduction in coherence with decreasing height due to surface effects is observed for all wind components, while being most pronounced for the vertical velocity. The coherence of the along-wind turbulence appears to be least sensitive to $\bar{z}$ and exhibits a noticeable dependence only at normalized wavenumbers $k\, d_z > 0.25$.
To account for the combined influence of measurement height and separation distance, the model coefficients A and C in Eq. (22) are fitted for a wide range of combinations across the bow-tie pattern. The resulting coefficients are shown in Fig. 20 as a function of the normalized separation $d_z\, \bar{z}^{-1}$.

Added Fig. 22

Line 482:
For lateral separations between 10 m and 90 m, one additional estimate is available both above and below this height from the diagonal segments connecting to the vertical line, as

Changes to manuscript (continued)

illustrated in Fig. 6. For $d_y = 60$ m, these estimates are located at $\bar{z} = 70$ m and $\bar{z} = 192$ m, and are compared to the $\bar{z} = 125$ m estimate in Fig. 22.
Although only three measurement heights are available and the estimates at the lowest and highest elevations are associated with relatively large uncertainty, a reduction in lateral coherence with decreasing measurement height is evident. Consistent with the vertical coherence results (Fig. 19), the height sensitivity is most pronounced for γ_{wy}. At $\bar{z} = 70$ m, the vertical velocity is quasi incoherent across the $d_y = 60$ m separation.

Referee comment

12. **Fig 18 a-c:** As mentioned in the text, a greater scatter is present for the horizontal components. For the sake of argument, let's say that for dz/z > 0.5, the curve fit provided by Eq 24 is no longer valid. The points used here range from z=55 to z=215, with a mean of 135m. If we use this mean value, it means that pair of points with dz > 67.5m fall on a region where the model does not perform well. If we get pairs of points that have a lower z there is a more significant restriction on the dz values. I ask the authors consider this and recommend a discussion on the validity of the model and if validity bounds should be given (especially for horizontal wind components).

We agree that the increased scatter at large normalized separations observed for the horizontal components, warrants a clearer discussion of the validity range of the proposed coherence model. Following the reviewer's suggestion, we have expanded the discussion in the revised manuscript to explicitly state the proposed validity bound of $d_j\,\bar{z}^{-1} \leq 0.5$.

Changes to manuscript

Line 467:
The exponential formulation in Eq. (24) provides an accurate fit to A_w. Greater scatter is observed for the horizontal components, particularly for $d_z\,\bar{z}^{-1} > 0.5$.

Line 550:
By introducing exponential relationships between the model coefficients and the normalized separation $d_j\,\bar{z}^{-1}$, a three-parameter coherence model is established.
While these exponential relationships provide accurate fits to the model parameters for the vertical velocity, increased scatter and deviations are observed for the horizontal components at $d_j\,\bar{z}^{-1} > 0.5$. The reduced accuracy at large normalized separations can primarily be attributed to the low data availability resulting from the limited size of the SRWS bow-tie pattern. The available measurements therefore support an application of the proposed coherence model for normalized separations of $d_j\,\bar{z}^{-1} \leq 0.5$. Additional measurements at larger separations are recommended for assessing and improving the model accuracy for the horizontal velocity components beyond this range.

Referee comment

13. **section 4.3.2 and Fig 20:** Can this be used to estimate lateral coherence from known vertical coherence? How good would that estimate be? Ultimately, we tend to obtain measureaments on a met-mast type of setup. The current setup investigated in this work is ideal to draw conclusions on how to estimate lateral from vertical.

We appreciate this comment and agree that estimating lateral coherence from vertical coherence would be a valuable application of the present dataset, particularly because vertical coherence can be obtained from conventional met-mast measurements more readily than lateral coherence. The comparison of the coherence model parameters for vertical and lateral separations in Fig. 23 provides a first indication of the relationship between the two and could potentially be used as a basis for such an approach. However, a thorough study of this relationship would require including additional separation distances and measurement heights than the ones shown in Fig. 23. Such a comprehensive study is beyond the scope of the present analysis but represents a very promising direction for future work. We have therefore added this aspect to the outlook of the manuscript.

Changes to manuscript

Line 562:
Further research could investigate methods for estimating lateral coherence from in-situ measurements of vertical coherence, enabling a more comprehensive characterization of atmospheric turbulence with limited measurement equipment.

3. Minor comments

Referee comment

1. Throughout the manuscript the notation "…" to indicate a range is used (e.g. u = 10…11 m/s). The ellipsis is not a common notation for ranges and I suggest the authors consider using a different notation.

We thank the reviewer for pointing this out. We have replaced the ellipsis ("…") throughout the manuscript by the word "to". For a detailed list of the resulting changes, we refer to our response to Reviewer #1, who raised the same issue.

Referee comment

2. **Line 38:** Please add a sentence clarifying what is meant by "horizontal asymmetry associated with reduced lateral coherence"

In this context, the term "horizontal asymmetry" refers to spatial differences in wind speed in lateral direction across the rotor associated with reduced coherence. We have clarified this in the revised manuscript.

Changes to manuscript

Line 38:
The horizontal asymmetry in wind speed across the rotor associated with reduced lateral coherence in the uniform shear model increases tower torsion, [...]

Referee comment

3. **Line 46:** numerical studies have shown that as well.

We agree with the reviewer and have added the suggestion to the manuscript.

Changes to manuscript

Line 47:
Field measurements and numerical studies indicate that spectral coherence varies across wind components, separation distance and direction, measurement height, and atmospheric stability.