# Response to a Public Comment on WES-2025-42 Impact of atmospheric turbulence on performance and loads of wind turbines: Knowledge gaps and research challenges Response to Etienne Cheynet

Branko Kosović, Sukanta Basu, Jacob Berg, Larry K. Berg, Sue E. Haupt, Xiaoli G. Larsen, Joachim Peinke, Richard J. A. M. Stevens, Paul Veers, and Simon Watson

## Response to Etienne Cheynet

We thank Prof. Cheynet for his comprehensive evaluation of our paper and valuable suggestions. The comments shown in blue font have been carefully considered, with our responses provided in magenta font and modified text shown in red font below. For context, unmodified text is shown in black font.

## Point 1: Definition of turbulence

It may be worthwhile to provide a clear definition of turbulence in this section. In wind turbine design and micrometeorology, turbulence is typically understood as three-dimensional and is clearly delineated by the spectral gap; motions on the low-frequency side of this gap are generally considered "non-turbulent" However, in mesoscale meteorology, such non-turbulent motions are sometimes described as two-dimensional turbulence. These differing definitions may create confusion for readers from diverse research backgrounds. It could be useful to clarify whether the analysis follows one convention or recognizes both. This could be done by referencing established literature or explaining how each definition applies within the context of the study.

To more clearly define the scope of the review we have expanded the following sentence in the introduction to more clearly define turbulence within the context of the manuscript:

> When considering turbulence impact on wind energy we adopt a broad view of atmospheric turbulence that is not focused only on irregular, chaotic, three-dimensional, small-scale motions in an ABL, but also includes larger-scale atmospheric forcings associated with quasi-geostrophic turbulence (e.g., Charney, 1971) and mesoscale phenomena (e.g., Lilly, 1983) that modulate turbulent flows in the ABL. Considering quasi-geostrophic turbulence is motivated by resulting ABL turbulence deviating from commonly made assumptions of stationarity, homogeneity, and Gaussianity.

## Point 2: Abstract

The sentence "Large-scale atmospheric circulations modulate the boundary layer turbulence, characterized by coherence and intermittence" appears to combine concepts that are not typically treated within the same theoretical framework. For example, coherence ($\neq$ coherent structure), a two-point statistical measure, used in signal processing, is typically applied under assumptions of stationarity and homogeneity. However, "intermittence" refers to transient events with sometimes extreme deviations from stationarity. These concepts do not comfortably coexist, and their combination here appears arbitrary. A clearer and safer formulation might be: “Large-scale atmospheric circulations and Earth surface characteristics modulate boundary layer turbulence.”

We did not modify the sentence “Large-scale atmospheric circulations modulate the boundary layer turbulence, characterized by coherence and intermittence.” In atmospheric boundary layers and boundary layers in general turbulence and coherent structures coexist and they are not independent of each other. Some of the examples are convective eddies and horseshoe vortices. Therefore, coherence and coherent structures are not independent concepts. Furthermore, coherence can be defined in the context of non-stationary flow and does not require the assumption of stationarity (e.g., Xue et al. 2025, GRL, 52, e2025GL114978. https://doi.org/10.1029/2025GL114978).

## Point 3: Manuscript organisation

The manuscript might benefit from a clearer structure based on the SGHET framework (stationary, Gaussian, homogeneous, ergodic turbulence), which has been used for wind turbine design. Sections 3.1 to 3.7 largely fall within this framework and could be presented as representing the current paradigm. Sections 3.8 and 3.9 begin to move beyond SGHET assumptions, but the transition is not clearly marked. Section 4 combines both SGHET-compatible and non-SGHET phenomena without always distinguishing between them. Section 4.2 is particularly interesting, as it addresses sub-mesoscale motions that lie outside the SGHET framework and are not accounted for in the idealized picture of a spectral gap separating microscale turbulence from mesoscale flows. This spectral gap is not always observed, suggesting potential coupling between scales. This coupling is often neglected in structural loading, but one that could be important for large offshore wind turbine design. Framing the manuscript around a progression from the SGHET framework to its limitations and potential extensions could improve clarity.

We have considered several approaches to organizing a complex topic treated in the manuscript. Each of them had some advantages and disadvantages. We agree that a possible organization of the manuscript could be by distinguishing between the stationary, Gaussian, homogeneous, ergodic turbulence (SGHET) paradigm that has been a dominant in analysis of turbulence impacts related to wind energy and non-SGHET. However, in our opinion, significant disadvantage of the proposed reorganization of the manuscript is that such organization would result in an unbalanced manuscript since a non-SGHET paradigm for wind energy applications is still in relatively early stage of the development. Instead, throughout the manuscript we emphasis the need to move beyond the SGHET framework.

## Point 4: Section 3.7 - Spectra and coherence

Within the SGHET framework, one-point spectra and coherence are the two main turbulence statistics — and arguably the only ones needed for wind load modelling. Indeed, turbulence intensity and integral length scales can be retrieved from the wind spectra. While there has been extensive work on modelling one-point spectra over the past sixty years, the authors have chosen to focus on a limited subset.

I tested the Tchen-Mikkelsen model a few years ago but could not reproduce the published results, despite the model's simplicity and appeal. Based on a private communication with Prof. Mikkelsen over six years ago, I believe there may have been an issue with the formulation of the equations in their original paper. I am not sure whether this has since been corrected. It is worth noting that Hu et al. (2018) also reported systematic deviations from the Kaimal model in the inertial subrange when using the Tchen-Mikkelsen formulation, which, by design, should not occur.

The final paragraph of Section 3.7 introduces the Davenport coherence model, a foundational contribution that perhaps deserves its own equation number and a proper citation to Davenport (1962). The value of the decay coefficient reported in line 273 (a $\approx$ 60) appears erroneous. Panofsky and Dutton (1984) reported values more typically in the range of a $\approx$ 12–15. The decay coefficient itself depends on the velocity component, atmospheric stability and the type of separation (longitudinal, vertical, or transverse). Bowen et al. (1983) also document a dependency on the separation distance and measurement height, which was also observed at the FINO1 platform (Cheynet, 2018). Solari and Piccardo (2001) provide a helpful overview of this parameter.

It is important to recall that the Davenport model was developed specifically for microscale turbulence, and decay coefficients reported in that context should be interpreted accordingly. While applying the Davenport model to mesoscale motions is acceptable, comparing decay coefficients for mesoscale and microscale motions, as done in lines 274–276 (page 13) does not make much sense ("comparing apples and oranges").

The text was modified as suggested. Text about Tchen-Mikkelsen spectral model was omitted. The equation for the magnitude of the coherence was added as well as related Davenport (1962) reference. The text was also modified to make sure that there is no intention to compare the Davenport model parameters between fully developed 3D turbulence and quasi-geostrophic turbulence (to avoid the appearance of "comparing apples and oranges"). The discussion of coherence was expanded and now includes Davenport's model as a standalone equation and the following text:

> Davenport (1962) estimated the parameter $a = 7$ for separation in both cross-wind and vertical directions. However, further studies demonstrated that the parameter $a$ is not constant but it depends on the atmospheric stability (e.g., Panofsky and Mizuno, 1975). While coherence analyses based on observations focused on mean wind direction, Berg et al. (2016) demonstrated how turbulence-resolving numerical simulations can be used to analyze coherence of three velocity components. They compared simulated non-Gaussian velocities to Gaussian fields and showed that their coherences are similar and found that as the separation increases the largest coherence switches from vertical to cross-wind component. While the longitudinal coherence is less important for a wind turbine design it is important for the turbine control (e.g., Schlipf et al., 2013). Thedin et al. (2023) used turbulence-resolving simulation driven by large-scale forcing derived from a mesoscale simulation to analyze coherence of three velocity components in three spatial directions and pointed to limitation of numerical simulations that do not resolve high-frequency fluctuations. For large-scale, quasi-geostrophic turbulence Vincent et al. (2013) analyzed coherence as function of separation and angle with respect to a mean wind direction using observations and mesoscale simulations. They extended a form of Davenport's coherence model to large separations that represent the coherence at mesoscale.

## Point 5: Coherence vs coherent structures

I think it would also be helpful for the authors to clearly distinguish between the terms "coherence" and "coherent structures". Coherence is a correlation function in the frequency space. It is a concept from signal processing used as a statistical measure, for example, to characterize the spatial correlation of wind velocity fluctuations. The coherence is used, among others, to generate spatially correlated turbulent wind fields for aeroelastic codes. Coherent structures: a more abstract term used to describe organized motions in a fluid. These terms refer to fundamentally different concepts, though they are sometimes conflated in the literature.

We have tried to make the distinction between coherent structures and coherence clear throughout the manuscript. However, we do not agree that coherence can be defined only within the SHGE turbulence framework (e.g. Chatterjee and Peet, 2021, Physics of Fluids). We have also modified one of the recommendations to address this comment:

> The characterization and quantification of effects of atmospheric stability, non-homogeneity, and coherent structures on turbulence non-

stationarity, ~~coherent structures~~ its coherence, and length scales and their impacts on the aerodynamic performance and wind turbine loads is still lacking.

## Point 6: Section 5

Maybe this section (atmospheric turbulence observations) could also be reorganized around the concept of the SGHET framework. This section could address the following question: which sensors allow for observations that go beyond this framework?

This section discusses sonic anemometer measurements and draws a parallel between Taylor's hypothesis and the eddy-covariance method. However, this comparison may risk some misinterpretation. The eddy-covariance method does not inherently rely on Taylor's hypothesis. It computes turbulent fluxes directly from time series and does not convert temporal measurements into spatial ones. In contrast, Taylor's hypothesis is generally used to infer spatial statistics from temporal data.

Section 5 should also make a clearer distinction between profiler lidars and scanning lidars. These are different instruments with different purposes. In my experience, this distinction is often overlooked. I have worked a little with scanning lidars in complex terrain, coastal sites and offshore, with both long-range pulsed and short-range continuous waves for the study of atmospheric turbulence. In my experience, the main takeaway is that long-range scanning lidars allow for qualitative analysis of turbulence. However, such lidars would struggle to quantify turbulence, especially spectral statistics, which are more useful than integral statistics. This is due to large probe volumes and low sampling frequencies. Short-range scanning lidars (e.g., WindScanners) are more promising, but unfortunately less commonly used and their useful scanning range is limited to 150-200 m.

Thus, section 5 could address a few more important knowledge gaps and research challenges: (1) it could explain if and how remote sensing could help move beyond the SGHET framework. (2) It could highlight key limitations of scanning lidars: probe volume averaging that can be large, low sampling rate, limited reliability, high cost, reduced performance if the flow across the probe volume is heterogeneous, and the fact that they measure the along-beam component only, which complicates the analysis of 3D turbulence.

The statement about Taylor's hypothesis was modified to explicitly state that the hypothesis is invoked when temporal measurements are used to infer spatial correlations. We considered expanding the discussion about lidars, but decided that this could lead to significant expansion of the manuscript beyond its current scope.

## Point 7: On the turbulence intensity and its relevance to wind loading

A common misconception in wind loading on structures (turbines, tower, bridges, etc...) is that the turbulence intensity is based on the standard deviation of the wind speed. For non-yawed turbines, it should be the standard deviation of the longitudinal component. The IEC 61400-1 standard itself is ambiguous on that point as it defines the turbulence intensity first based on the standard deviation of the wind speed and later on, using the longitudinal wind velocity component.

For wind loading on structures, the turbulence intensity is, fortunately, not absolutely necessary. Within the SGHET framework, only three wind statistics are needed to generate a spatially correlated wind field: the mean wind speed, the one-point velocity spectra and the coherence of turbulence. The turbulence intensity can be directly retrieved from the velocity spectra and the mean wind speed. In the Eurocode (EN 1991-1-4: Eurocode 1), the turbulence intensity is defined based on the roughness length, which makes more sense from a modelling viewpoint. However, if I remember properly, the Eurocode is only usable for ultimate limit-state design (strong wind), for which the atmosphere is assumed neutral.

Another weakness of turbulence intensity as a statistic is that it is inversely proportional to wind speed. This property is not desirable for a non-dimensional turbulence metric usable in wind loading. In my opinion, the possible overreliance on turbulence intensity in wind turbine design is a weakness of the IEC standard. The turbulence intensity is a tricky quantity to use: it is widely used, it is easy to measure and interpret, but has multiple definitions depending on the user's background. Finally, it has limited physical meaning and is less informative than the velocity spectra. A possible alternative could be the use of standard deviation profiles, which would depend on surface roughness, atmospheric boundary layer depth and thermal stratification of the atmosphere. However, this would require new measurement techniques for validation, with sensor heights extending beyond those of traditional mast-based observations.

Based on the comment, the following sentence was added to the first paragraph of the subsection "Impact of Atmospheric Phenomena on Fatigue Loads:"

> However, the IEC 61400 standard does not define turbulence intensity consistently. First it defines it based on the wind speed and later based on the longitudinal velocity.

Also, in the second paragraph we added the following statement:

> By definition turbulence intensity is inversely proportional to wind speed and therefore under certain extreme wind conditions, such as downslope wind storms (Pehar et al., 2019), it is not a good predictor of fatigue loads.

## Point 8: On the assumption of stationarity and Gaussianity

In non-stationary (intermittent) flows, non-Gaussianity often arises as a direct consequence of the lack of stationarity. Skewness and kurtosis are two commonly used metrics to quantify deviations from Gaussian behaviour. They rely on the assumption of stationarity. Therefore, their calculation in intermittent flows has limited physical meaning. In other words, once the flow is non-stationary, traditional statistical moments may no longer be applicable, and alternative analysis tools are needed. This raises two key questions: (1) Under which conditions do we observe stationary, non-Gaussian flows in the atmosphere, and how do they affect wind turbine loading? (2) Which tools can be used to study non-stationary atmospheric flows in the context of wind turbine design?

The second question has started being addressed in wind engineering since the 2010s, where researchers often decompose the flow into stationary and non-stationary components using tools such as empirical mode decomposition. Similar approaches could be valuable for advancing wind turbine load analysis beyond the SGHET framework. Maybe I should clarify that the field of wind engineering and wind energy are overlapping but distinct.

We disagree with the implication that intermittent flows are necessarily non-stationary. Turbulent flows characterized by intermittency (long tail probability distributions) can be stationary. This intermittency (of different turbulence properties, e.g., velocity increments) is distinguished from global intermittence observed in stably-stratified atmospheric boundary layers frequently a consequence of breaking Kelvin-Helmholtz waves. We make the distinction between turbulence intermittency and global intermittency clear at the end the subsection 3.6 "Statistical Hierarchy, Spectra, and Coherence":

> This statistical intermittency must be distinguished from the global intermittency induced by large coherent structures such as, for example, Kelvin-Helmholtz billows.

## Point 9: On the Integral length scales (section 3.6)

Integral length scales (ILS) are useful in wind tunnel studies. For mast-based measurements, ILS are typically estimated in the streamwise (x) direction. Following Panofsky and Dutton (1984), page 176, the use of ILS in atmospheric studies should be avoided due to their lack of reliability. I tend to agree with them. In my opinion, estimates of ILS are fairly reliable for the vertical velocity component, but much less so for the horizontal components. As the authors correctly point out, this is largely due to the influence of large-scale eddies on the auto-correlation function. Obtaining better estimates would require a longer time series, but this can conflict with the assumption of stationarity, potentially compromising the validity of the ILS estimation itself.

It can be noted that there are multiple methods to estimate the ILS, not limited to the use of the autocorrelation function. These methods can lead to quite different values. For example, in wind engineering, the so-called von Kármán spectrum uses ILS as an input parameter, which can be estimated by least-squares fitting to measured power spectral densities. Overall, I think the section could reflect more critically on the relevance of ILS for wind turbine design. Are they truly useful? If they are not reliable, should we consider alternative length scales? And if so, which ones? These are open questions, and while I don't claim to have clear answers, I believe they are important to raise.

ILSs are important in characterizing turbulence. They are parameters in IEC spectral models. They are also used in turbulence modeling and therefore, at least indirectly, relevant for wind turbine or wind farm design. We have added the following text to the end of the subsection:

> Related to sparsity of data needed to estimate ILSs is the challenge to determine them from the data. Considering these challenges, a different way to estimate relevant turbulence length scales would be beneficial. LES can provide data needed to estimate all the integral length scales. Stanislawski et al. (2023) used LES of aytime ABLs under different atmospheric stability conditions to study the effect of turbulent inflow ILSs on wind turbine loads. They found that loads increase with increasing length scales. Hodgson et al. (2025) analyzed LESs of a flow through a wind turbine array and concluded that the power output of a wind farm depends integral lengths scales of turbulent inflow.

## Point 10: Section 8.1

Over the years, I have frequently seen authors refer to Kaimal et al. (1972) as the source of both the so-called IEC-Kaimal spectral model and the exponential decay model for coherence. However, a close reading of Kaimal et al. (1972) shows that coherence was not investigated in that study. The foundational work on turbulence coherence was conducted earlier by Panofsky and co-authors, as well as by Davenport during the 1960s and 1970s. In addition, the one-point spectral model presented in Kaimal et al. (1972) differs significantly from the version adopted in the IEC standard.

Based on the comment the text was modified as follows:

> ... the Kaimal spectral (Kaimal et al., 1972) with the exponential coherence model by Davenport (1961).

## Point 11: Lines 882–884

The statement that the IEC Kaimal model becomes height-independent above 60 meters is "not physically realistic" might benefit from a more nuanced phrasing. This height-independence is a reasonable simplification that reflects the properties of the mixing layer. Above the surface layer, spectral characteristics often no longer scale with height, and assuming continued height dependence may be less realistic. Paradoxically, the IEC simplification may offer a more accurate representation than surface-layer spectral models that enforce height scaling throughout.

As can be seen from Figure 6 in the manuscript, the longitudinal integral length scale of the streamwise velocity component varies with height computed based on LES of a neutrally stratified ABL. This length scale is a parameter in Kaimal spectrum as outlined in IEC standard where it is prescribed as constant above 60 m. Similarly, the longitudinal integral length scale of the streamwise velocity in a stably stratified ABL also varies with height. We have modified the text to qualify the statement:

> ...this assumption is not physically realistic for modern rotors, in particular when operating in a relatively shallow stably-stratified ABL.

## Point 12: Lines 885–888

The logical connection between the two sentences in this paragraph seems flawed. The sentence beginning with "However, wind turbines in the field are subject to atmospheric turbulence..." appears to contrast with the previous sentence describing how turbulence is simulated using stationary, Gaussian wind fields. But there is no contradiction here. Simulations based on the SGHET framework are intended to approximate atmospheric turbulence.

A formulation that corrects that issue and highlights the limits of the SGHET framework would read as "According to IEC standards, standard industry tools such as TurbSim (Kelley and Jonkman, 2007) and the Mann turbulence generator (e.g., Dimitrov et al., 2024) generate stationary homogeneous Gaussian turbulent wind fields. While these models are widely used for design and simulation, actual atmospheric turbulence experienced by wind turbines can exhibit strong nonstationarity and non-Gaussian characteristics, which may significantly affect power output, structural loading, and fatigue life."

We have rewritten the paragraph about TurbSim to more clearly distinguish coherent structures included in TurbSim from random coherent turbulence as follows:

> Working towards this goal, researchers from ~~NREL developed the~~

> ~~TurbSim (Jonkman, 2009) stochastic inflow turbulence tool. This tool has been developed to provide a numerical simulation of a full-field flow that contains coherent turbulence~~ the National Renewable Eenergy Laboratory (NREL) (Jonkman, 2009) implemented in TurbSim a capability to include coherent structures that reflect the proper spatiotemporal turbulent velocity field relationships seen in instabilities associated with nocturnal boundary layer flows (e.g., breaking Kelvin-Helmholtz waves) and which are not represented well by the IEC Normal Turbulence Models. TurbSim provides the ability to efficiently generate randomized coherent turbulent structures produced by one of the non-neutral spectral models that are superimposed on the more random background turbulent field characterized by non-zero coherence ~~as produced by one of the non-neutral spectral models~~.

## Point 13: Lines 897–902

The paragraph describing TurbSim may give a misleading impression regarding its relationship to the SGHET framework. While the tool does allow for the superposition of randomized coherent turbulent structures, the underlying turbulence field is still generated within the SGHET paradigm. That is, it remains stationary, Gaussian, and homogeneous, constructed from predefined spectra and coherence functions. It is important to clarify that coherence structures are always present in TurbSim-generated fields due to the use of a coherence function; this is not unique to the added structures. Coherent structures refer to organized, persistent patterns of motion. They can be turbulent or non-turbulent motion. These structures are spatially and temporally correlated regions of the flow, e.g. vortices, shear layers, or streaks, that carry a significant portion of energy and contribute to the transport of momentum, heat, or scalars. Unlike statistical coherence, which describes correlations between signals, coherent structures are physical features within the turbulent flow.

The superposition of optional deterministic coherent structures can indeed help represent flows beyond the scope of traditional models like the IEC Normal Turbulence Model. In that sense, TurbSim offers a useful extension. Maybe the paragraph could better distinguish between the base SGHET-generated field and the additional non-SGHET structures. This clarification would help avoid confusion regarding what constitutes a true move beyond the SGHET assumptions.

We agree that coherent structures are physical feature of a flow, and they can be integral components of a turbulent flow, or they can modulate turbulent flows (e.g. tropical cyclones). The coherence is a quantitative measure characterizing turbulent flow. While coherence is commonly defined as a Fourier transform of a correlation function it is possible to define coherence of an inhomogeneous turbulent flow using different, local basis functions based on its physical manifestation through correlation functions.

## Point 14: Lines 912–923

The discussion on quad-coherence and its impact on wind loading is interesting but appears somewhat speculative. As discussed in Cheynet et al. (2022), quad-coherence typically may have little to no influence on wind loading when linearized load models are used. Its relevance for nonlinear loading remains less clear. A recent study by Wang et al. (2025) investigated the role of out-of-phase fluctuations on wind-induced forces on floating bridges, which might offer some insight here.

It is also worth noting that specific modelling of quad-coherence is not strictly required for wind field simulation using the IEC Kaimal spectrum with exponential decay. As shown in (eqs. 28-29 Cheynet et al., 2022), quad-coherence can arise implicitly through the use of a complex exponential phase term in the coherence function. This produces vertical quad-coherence but not lateral quad-coherence unless yaw misalignment is introduced. Similarly, the uniform shear model without blockage (Mann, 1994) also exhibits vertical but not lateral quad-coherence.

Given this, it might be helpful to refine the paragraph to reflect that while quad-coherence can be present and included in some models (like the Mann model), its practical significance for wind turbine loading, particularly in standard design methodologies, remains uncertain.

The following text was added to address the comment:

> The algorithm windSim4D developed by Cheynet et al. (2022) includes quad-coherence and relaxes Taylor's frozen turbulence requirement. Cheynet et al. (2022) indicated that quad-coherence does not affect linearized wind load estimates.

## Point 15: Lines 928–934

An important aspect to consider when combining mesoscale and microscale motions is that such models generally assume the two scales are uncoupled, relying on the presence of a clear spectral gap. If I remember well, the model by Syed and Mann (2024) follows this assumption and was developed specifically for neutral conditions; it may also be valid under stable stratification. However, under convective (unstable) conditions, the separation between scales often breaks down, and interactions between mesoscale and microscale motions become apparent. In such cases, the assumption of scale independence may no longer hold, and the applicability of this type of model becomes uncertain. I believe this limitation should be more clearly highlighted in the discussion, especially given the relevance of convective boundary layers in wind energy research.

The following sentence was added to address the comment:

> Further developments are needed to include conditions when mesoscale peak is not pronounced such as in the presence of mesoscale convective circulations.

## Point 16: Section 8.3

I believe this is one of the most important sections of the manuscript and may deserve further elaboration. A significant research gap in wind loading, particularly from a structural dynamics perspective, is the continued emphasis on undisturbed, upstream flow conditions. In practice, many wind turbines — especially in large farms — operate in the wake of other turbines, where the flow may not be stationary, Gaussian, or homogeneous. This calls for a move beyond the SGHET framework commonly used in wind turbine design.

Most turbulence generators assume at least statistical stationarity or spatial homogeneity. However, in wind farm wakes, these assumptions are often violated, raising the question of whether our current tools are still appropriate. There is a clear need for new turbulence characterization methods that can account for turbulence in the wake of turbines, particularly in the context of wind loading and fatigue. While I am not an expert on FAST.Farm (I could misunderstand it), it appears to offer a promising middle ground by capturing key wake dynamics and turbulence advection in a computationally efficient framework that may be suitable for load analysis.

Following a comment by one of the reviewers we have removed subsection 8.3. We agree that the topic of wake generated turbulence is important and deserves significant attention. In fact, it is treated in another paper in preparation for the Grand Challenges series. In this manuscript we focus on the atmospheric boundary layer turbulence encountered by the first row of turbines.

## Point 17: Section 8.6

I think this section should begin by clearly restating the prevailing paradigm under which turbulence is used in wind energy, namely, the assumption of stationary, Gaussian, and homogeneous turbulence. Framing the conclusion around this paradigm would help emphasize the need to move beyond it. Specific pathways for doing so, whether through new models, observational techniques, or analytical tools, would make the call to action more concrete. As it stands, the list of recommendations feels somewhat disjointed, and organizing it around a clear logical structure would significantly improve its clarity.

The list of recommendations is organized based on the current structure of the manuscript (and not SGHET – non-SGHET structure) to emphasis the need to consider the whole range of atmospheric scales of motion when addressing turbulence impacts on power production and wind turbine loads. Therefore, the list starts with the need to consider and observe mesoscale motions that modulate ABL turbulence followed by how they affect properties of ABL turbulence when assessing impacts on wind farms, etc.

## Point 18: Line 1185

The phrase "mesoscale-generated turbulence associated with low-level jets, convective cells, convective rolls, and gravity waves" seems to conflate turbulence with larger-scale organized motions. In wind engineering and micrometeorology, such features are not considered turbulence themselves but rather mesoscale flow structures that can interact with or trigger turbulence under certain conditions. It may be helpful to clarify this distinction to avoid confusion between mesoscale motions and (microscale) turbulent fluctuations.

To clarify the statement the phrase "mesoscale-generated turbulence associated with low-level jets, convective cells, convective rolls, and gravity waves" was modified to:

> Mesoscale-~~generated~~modulated turbulence associated with low-level jets, mesoscale convective circulations (convective rolls and convective cells), and gravity waves ~~are~~is observed onshore and offshore.

## Point 19: Line 1190

This line attempts to address multiple concepts: atmospheric stability, turbulence characteristics, and turbine performance, in a single sentence, which results in ambiguity. It also groups "turbulence," "coherent structures," and "length scales" together in a way that conflates concepts at different levels. Turbulence is a flow regime, coherent structures are organized motions that may or may not be part of turbulent flow, and length scales are statistical measures used to characterize turbulence. These should be more clearly distinguished, as they represent different aspects of atmospheric dynamics.

The sentence was modified as follows:

> The characterization and quantification of effects of atmospheric stability, non-homogeneity, and coherent structures on turbulence nonstationarity, ~~coherent structures~~ its coherence, and length scales and

their impacts on the aerodynamic performance and wind turbine loads is still lacking.

## References


Berg, J., Natarajan, A., Mann, J., and Patton, E. G. (2016). Gaussian vs non-gaussian turbulence: impact on wind turbine loads. *Wind Energy*, 19(11):1975–1989.

Chatterjee, T. and Peet, Y. T. (2021). Streamwise inhomogeneity of spectra and vertical coherence of turbulent motions in a finite-size wind farm. *Phys. Rev. Fluids*, 6:114601.

Cheynet, E., Daniotti, N., Bogunović Jakobsen, J., Snæbjörnsson, J., and Wang, J. (2022). Unfrozen skewed turbulence for wind loading on structures. *Applied Sciences*, 12(19).

Davenport, A. G. (1961). The spectrum of horizontal gustiness near the ground in high winds. *Q. J. R. Meteorol. Soc.*, 87(372):194–211.

Davenport, A. G. (1962). The response of a slender line-like structure to a gusty wind. *Proceedings of the Institution of Civil Engineers*, 23:389–408.

Hodgson, E. L., Troldborg, N., and Andersen, S. J. (2025). Impact of freestream turbulence integral length scale on wind farm flows and power generation. *Renewable Energy*, 238:121804.

Jonkman, B. J. (2009). TurbSim User's Guide: Version 1.50. Technical Report NREL/TP-500-46198, National Renewable Energy Laboratory, Golden, CO.

Kaimal, J. C., Wyngaard, J. C., Izumi, Y., and Coté, O. R. (1972). Spectral characteristics of surface-layer turbulence. *Q. J. R. Meteorol. Soc.*, 98:563–589.

Panofsky, H. A. and Mizuno, T. (1975). Horizontal coherence and pasquill's beta. *Boundary-Layer Meteorol*, 9:247–256.

Pehar, B., Zlomušica, E., and Zalihić, S. (2019). The turbulence intensity of the wind bora. In Karabegović, I., editor, *New Technologies, Development and Application*, pages 369–376. Springer.

Schlipf, D., Cheng, P. W., and Mann, J. (2013). Model of the correlation between lidar systems and wind turbines for lidar-assisted control. *Journal of Atmospheric and Oceanic Technology*, 30(10):2233 – 2240.

Stanislawski, B. J., Thedin, R., Sharma, A., Branlard, E., Vijayakumar, G., and Sprague, M. A. (2023). Effect of the integral length scales of turbulent inflows on wind turbine loads. *Renewable Energy*, 217:119218.

Thedin, R., Quon, E., Churchfield, M., and Veers, P. (2023). Investigations of correlation and coherence in turbulence from a large-eddy simulation. *Wind Energy Science*, 8(4):487–502.

Vincent, C. L., Larsén, X. G., Larsen, S. E., and Sørensen, P. (2013). Cross-spectra over the sea from observations and mesoscale modelling. *Bound.-Layer Meteorol.*, 146:297–318.