Reviewer #2 Response Letter for WES-2025-42 Impact of atmospheric turbulence on performance and loads of wind turbines: Knowledge gaps and research challenges

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 Reviewer #2

We thank the reviewer for their time and evaluation of our paper. We have carefully read these comments (shown in blue font) and provided below point-by-point responses (shown in magenta font) and the modified text (shown in red font) below. For context, in some instances we included text that was not modified (shown in black font).

This manuscript provides an extensive review of the role of the atmosphere in power capture and loads of wind turbines. This manuscript includes essential information for a general reader to be informed about the main phenomena associated with this wind energy topic, and it can be a valuable resource for our research community as well.

We thank the reviewer for their positive remarks.

1. Each section tackles, in more or less depth, a specific related topic by providing a summary of the associated recent literature. Finally, a very brief outlook on the related research is provided in the final section 8.6. I would propose to restructure each section including a summary of the recent research achievements (rather than listing the executed works), then illustrating the current research gaps, and the research projects/tasks needed to address those gaps. This writing approach is sometimes outlined in a few sections, but generally not implemented in most of the sections.

In the revised manuscript we followed reviewer's suggestions. Since the manuscript can be viewed as consisting of two parts: the first part including relevant background, while the second part addresses the impact of atmospheric turbulence on wind power production and loads, to address reviewer's comment we have therefore focused on the second part. We have added paragraphs addressing research gaps to the subsection 7.3.1

> Although LLJs and their impacts on wind energy have been studied extensively in specific regions (e.g. Emeis, 2014; Aird et al., 2022), there is still a lack of observed wind speed and direction profiles associated with LLJs, particularly for offshore and coastal conditions Shaw et al. (2022). Towers typically only reach 100-200 m, and frequently sodars are ineffective in the layer near the LLJ nose due to the lack of shear-produced turbulence. While profiling (floating) lidars can provide more information, they are expensive and not routinely used and typically have a vertical range of approximately 200 m. These measurements should also provide more information about the turbulence structures near and above the LLJ nose.

and the subsection 8.5

> Turbine incidents and failures are underreported. There are only a few data mining studies of wind turbine failures and accidents based on textual analysis of news reports (e.g., Ertek and Kailas, 2021). There is a need for creation of a comprehensive database of failures for better assessment of the impact of extreme events on individual wind turbines and wind farms and for more accurate risk assessment.

2. Some effort should be made to homogenize this extensive manuscript. Currently, it reads as a collection of various drafts written by different authors with different writing styles connected by their content. As I understand this was a necessary strategy to work on such an extensive manuscript, at the same time, I believe an extra effort should be made to homogenize the writing, avoid potential overlaps, and cross-reference different sections when possible.

We have made effort to homogenize the manuscript by eliminating subsection 8.2.2 and 8.3 in the original manuscript, merging subsection 3.1 and 3.2 into a new subsection 3.1 and subsection 3.7 and 3.9 into a new subsection 3.6, as well as partially rewriting or extending several sections (e.g., 4.1 "Low-level Jets," 5. "Observing ABL Flows," 6. "Modeling of ABL Flows," 7.1 "Power Curves," 8.2 "Impact of Atmospheric Phenomena on Fatigue Loads," 8.5 "Extreme Events and Loads," so that the overall structure of the manuscript is more uniform.

3. The manuscript is very extensive and, sometimes, some discussions are rather shallow and could be omitted (see details below). I would suggest revising critically the manuscript to identify those sections/parts that can be removed, merged, or shortened without omitting important information for the reader. Some detailed comments are reported in the following.

Following reviewer's comment we have eliminated subsections 8.2.2 "Global Intermittency and Coherent Structures" and 8.3 "Wind Farm Generated Turbulence." We have merged subsection 3.2 "Turbulence Quantities of ABL flows with subsection 3.1 into the new subsection 3.1 "Mean and Turbulence Quantities of ABL flows."

1. L57 The turbulent motions....To my knowledge (e.g. PERRY, A.E. & MARUSIC, I. 1995 A wall-wake model for the turbulence structure of boundary layers. Part 1. Extension of the attached eddy hypothesis. J. Fluid Mech. 298, 361–388.; HÖGSTRÖM,U., HUNT, J.C.R. & SMEDMAN, A.S. 2002 Theory and measurements for turbulence spectra and variances in the atmospheric neutral surface layer. Boundary-Layer Meteorol. 103 (1), 101–124; Van der Hoven (1957) for the spectral gap) turbulent motions have a specific spectral footprint and are restricted to scales smaller than those belonging to the mesoscale range. I think you should replace the adjective turbulent with atmospheric.

As suggested by the reviewer we have replaced "turbulent" with "atmospheric".

The sentence now reads as follows:

> The atmospheric motions exhibit three distinct kinetic energy scaling ranges, starting from the largest planetary waves and synoptic scales through mesoscale to microscales in the ABL depicted in Fig. 1.

2. L79 – You can merge it with the previous paragraph.

The paragraph was merged.

3. L108 – Check for typos.

Typo corrected.

4. L192-194 – Specify the criterion used in Kelley et al. (2006) to identify neutral conditions.

The report states only that:

> "Neutral conditions ($Ri_g = 0$) represent a flow in which turbulence is being generated only through the action of wind shear; buoyancy has no influence."

We have therefore decided to remove the statement and the related citation.

5. Sect. 3.9 is very disconnected from the rest of the discussion. Maybe it can be removed.

Subsection 3.9 was removed. The text defining statistical analysis tools was added to the beginning of subsection 3.8 where we think it represents a proper introduction to spectra and cospectra of turbulent quantities.

6. L464 – Please add that sonic anemometers typically measure virtual temperature as well. This physical parameter is leveraged for the estimation of the friction velocity and Obukhov length through the eddy-covariance method.

We have added the following sentences:

> When combined with independent temperature measurements, sonic anemometers can provide high-rate measurements of acoustic temperature which represents a good approximation of a virtual temperature which accounts for the water vapor in the air. By simultaneously measuring velocity components and virtual temperature, using the eddy-covariance method sonic anemometers can provide

sensible heat fluxes. Using measurements of momentum fluxes and sensible heat fluxes one can estimate the Obukhov length.

7. L559 – Add here the reference to the IEC standards, which is provided at L 585, instead.

Reference was added.

8. L655 – Provide details on the Langevin equation.

The Langevine equation and definition of terms in the equation were added:

Using highly fluctuating data at 1 Hz or higher, it could be shown that power characteristics can be defined using stochastic process modeling representing the evolution of a random value based on the Langevin equation 1.

$$\frac{dP(t)}{dt} = D_1(P,u) + \sqrt{D_2(P,u)}\Gamma(t) \quad (1)$$

Here, $P(t)$ denotes the power output, $D_1(P,u)$ is the drift coefficient, $D_2(P,u)$ is the diffusion coefficient, and $\Gamma(t)$ denotes the zero-mean Gaussian noise. The coefficients are functions of the power output P and the wind speed u.

9. L656 – Fix references.

References were fixed.

10. L721 – Wind Energy, no need for capital letters.

Capital letters were changed to lower case.

11. Sect. 8.2.2 does not provide a clear explanation of the phenomenon described. I would suggest removing it.

Global intermittence of a stably stratified boundary layer is an important physical phenomenon that can impact turbine loads. The phenomenon is briefly described in the subsection 3.1.8 where references are provided. We therefore think that this topic should be addressed. We followed reviewer's suggestion and removed the subsection 8.2.2, but included the following text in the subsection 8.1 "Impact of Atmospheric Phenomena on Fatigue Loads."

In Section 3.7, the global intermittency phenomenon was briefly introduced. Even though these phenomena are often present in the atmosphere, only a few studies have described their impacts on wind turbine loading. Using observational data from the Long-Term Inflow and Structural Test (LIST) project, Kelley (2011) documented severe transient loading events associated with turbulent bursting events (see Fig. 15 for an example). In an LES study, Park et al. (2015) reported the presence of global intermittency in stable boundary layers. They found that these structures led to strong asymmetric forces on the rotor and, in turn, produced increased tower-top yawing moments.

12. Similarly for Sect. 8.3. The discussion is very generic and no critical information is provided.

We have removed the subsection 8.3.

References

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