Reviewer #1 Response Letter for WES-2025-42 Impact of atmospheric turbulence on performance and loads of wind turbines: Knowledge gaps and research challenges

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Response to Reviewer #1

We thank the reviewer for their time and evaluation of our paper. We have carefully read these comments (shown in blue font) and provided 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).

The submitted paper reviews the fundamentals of atmospheric flow from global to microscale, and then zooms in on mesoscale and microscale turbulence and their impact on wind turbines. As turbines continue to grow in size and deployment, this review is timely and important to highlight the need to revisit commonly used assumptions/simplifications. Overall, the paper is well-written and is an especially impressive effort coordinating many authors. There are several areas that can be improved with further integration across the paper, I've noted a few below, where the text repeats or contradicts itself. I hope the authors may consider these comments in a revision.

We thank the reviewer for their positive remarks.

The authors have made a choice to focus the review on ABL effects on wind turbines, rather than wind farms. This is a reasonable choice to keep the paper's scope constrained, but wind turbines are nearly always placed in wind farms, where wake and array level effects will both depend on the ABL in interesting/complex ways and also will change many aspects discussed (i.e. in large wind farms, the effect of ABL turbulence on the loads of the leading row described extensively in Sections 7 and 8 could matter less than the interaction between the ABL flow and wakes/farm-scale effects that will dictate the performance of downwind turbines, of which there are many more than there are leading row turbines usually). My specific suggestion would be to confront the scope of the paper in the introduction and conclusions/recommendations to highlight this focus on wind turbines rather than arrays.

The following text (shown in red font) was added to the introduction to more clearly define the scope of the manuscript:

> When considering turbulence impact on wind energy we adopt a broad view of the 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.

and

> Our review focuses on the impact of turbulence on a single wind turbine rather than wind turbine arrays. The impacts of turbulence generated by wind turbine and wind farm wakes as well as turbine and farm control are addressed in companion papers in the "Grand Challenges: wind energy research needs for a global energy transition" series.

There is some inconsistency in the degree to which topics are introduced in a simple way through text description versus quantitative measures. For example, first order statistics, shear, and TKE are described completely, whereas Reynolds decomposition, integral length scale, energy spectra, etc. are not as clearly introduced quantitatively. Please consider making the technical descriptions more uniform.

We merged the subsections 3.1 and 3.2 and addressed the comment by adding information about Reynolds decomposition and turbulent fluxes. The subsection 3.1 now reads:

3.1 Mean and Turbulence Quantities of ABL flows

Instantaneous velocity components along the longitudinal, lateral, and vertical directions are commonly denoted by, u, v, and w, respectively. In addition to velocity components, relevant thermodynamic variables: pressure, p, temperature, T, and water vapor mixing ratio, q determine atmospheric stability. Using these thermodynamic variables one can derive: the virtual temperature, the potential temperature, and the virtual potential temperature. The virtual temperature, T_v, is a temperature at which pressure and density of a dry air parcel are equal to the moist air one. The potential temperature, θ, is a temperature a parcel of fluid would attain when adiabatically brought to a reference pressure (e.g., standard surface pressure, usually $p_0 = 1{,}000$ hPa), while the virtual potential temperature also accounts for the effects of water vapor.

$$T_v \approx T(1 + 0.608q); \qquad \theta = T\left(\frac{p_0}{p}\right)^{\frac{R}{c_p}}; \qquad \theta_v \approx \theta(1 + 0.608q)$$

Here, R is the ideal gas constant and c_p is specific heat capacity at the constant pressure.

Ensemble mean values of a variable φ are represented by an overline, $\overline{\varphi}$. Since it is difficult to estimate an ensemble mean, in the wind energy community it is common practice to approximate it by a temporal, spatial, or combined spatio-temporal average. When conditions are nearly spatially homogeneous or temporally stationary Reynolds decomposition of instantaneous values, φ into mean and fluctuating quantities is applicable.

$$\varphi = \overline{\varphi} + \varphi'$$

Spatial or temporal mean values of a variable φ are represented by an overline, $\overline{\varphi}$. The mean velocity components are $\overline{u}$, $\overline{v}$, and $\overline{w}$ and the mean potential temperature is $\overline{\theta}$.[1] Here overbar represents either temporal or spatial average or combined spatio-temporal average. The mean horizontal wind speed is: $U = \sqrt{\overline{u}^2 + \overline{v}^2}$. Henceforth, the mean wind speed at hub height will be denoted as U_H.

Reynolds decomposition is commonly used to define turbulence quantities including turbulent kinetic energy and turbulent fluxes of momentum and heat. The three components of velocity variances are denoted as σ_u^2, σ_v^2, and σ_w^2, respectively. Turbulence kinetic energy (TKE; $\overline{e}$) is computed as:

$$\overline{e} = \frac{1}{2}\left(\sigma_u^2 + \sigma_v^2 + \sigma_w^2\right)$$

The turbulence intensity is more commonly used in the engineering community. The turbulence intensity It is frequently defined along the streamwise direction: $I = \sigma_u/U$. or accounting for the full horizontal wind. $\sqrt{\sigma_u^2 + \sigma_v^2}/U$. The covariances $\overline{u'w'}$, $\overline{v'w'}$, and $\overline{u'v'}$ represent the components of momentum fluxes (closely related to Reynolds stress components); the sensible heat fluxes are denoted by $\overline{u'\theta'}$, $\overline{v'\theta'}$, and $\overline{w'\theta'}$.

Frequently flow conditions are not stationary or homogeneous. Multiresolution decomposition was developed for such conditions (e.g., Treviño and Andreas, 1996; Howell and Mahrt, 1997). Turbulence characterization under non-stationary and non-homogeneous conditions is challenging and requires careful consideration, it is currently a very active area of research (e.g., Lehner and Rotach, 2023; Arias-Arana et al., 2024).

We have also added definitions of the correlation function and the integral length scale (ILS) tensor in the subsection 3.5:

The ILS, which is usually estimated using correlation functions. A spatial autocorrelation function for a turbulent quantity φ is defined as:

$$\rho_{\varphi\varphi}(\mathbf{x}, r\mathbf{e}) = \frac{\overline{\varphi'(\mathbf{x})\varphi'(\mathbf{x} + r\mathbf{e})}}{\overline{\phi'(\mathbf{x})^2}}$$

Here, ρ is a spatial correlation function of a variable φ at point in space $\mathbf{x}$, r is a distance from $\mathbf{x}$ along the direction of the unit vector $\mathbf{e}_\alpha$, and the overline denotes the ensemble average. In case of spatially homogeneous flows

[1] In the atmospheric science literature, a different convention is followed. There, $\overline{u}$ and $\overline{v}$ represent zonal and meridional velocity components, respectively.

the ensemble average can be replaced with the spatial average, while in case of statistically stationary flows it can be replaced with the time average. The ILS of a variable φ along the direction α is then defined as:

$$L_{\varphi}^{\alpha} = \int_{0}^{\infty} \rho_{\varphi\varphi}(\mathbf{x}, r\mathbf{e}_{\alpha})dr$$

There seems to be no substantial discussion of the boundary layer height, which plays a critical role for wind farms, aside from a limited discussion in conjunction with gravity waves in Section 7.3.3. The boundary layer height may also play an increasing role for individual turbines (focus of this review) as well, given the growing size of turbines mentioned many times, and the potential operation in shallow marine/stable boundary layers.

The following text addressing the comment about the boundary layer height was introduced in the subsection 3.1 (originally subsections 3.1 and 3.2):

Another parameter that characterizes an ABL is its height. While there is no single definition of the boundary layer height, it is commonly defined as a level above the surface where either TKE drops below some threshold or, alternatively, a level where the potential temperature gradient exceeds a certain value and forms a capping inversion. In the literature, the heights of the low-level jets are also used as surrogates of stable boundary layer heights. The ABL height is commonly denoted with h, while the convective, mixed layer height is frequently denoted with z_i. Under strong convective conditions a well mixed boundary layer height can exceed 3 km, while under stably stratified conditions with wind speeds greater than 3 m s^{-1} (when wind turbines produce power) a boundary layer height can be as low as several tens of meters, i.e., below the hub height of a modern utility scale with turbine. To characterize wind turbine operating environment under stably stratified conditions the boundary layer height must be taken into consideration. While the boundary layer height can be inferred from remote sensing observations, direct observations are generally not available. This represents a challenge when estimating turbulence impacts on wind turbine performance since the wind shear and the turbulence level impacting turbine blades can vary significantly through a rotor rotation depending on the ABL height. Puccioni et al. (2024) used observations with a scanning lidar from the AWAKEN field campaign to assess ABL height. In a simulation study, Park et al. (2014) documented the influence of low-level jet heights on wind shear and turbulence intensity, and in turn, how these variables affect various turbine loads.

1. Line 14: In paragraph 1, the framing describes that wind resource is typically assessed using 10 min averaged hub height wind speed. Then commentary is made regarding turbulence timescales. I also thought this would be a good

place to mention ABL shear (mentioned in abstract).

Following reviewer's suggestion, in addition to wind speed (and direction), wind energy resource assessment also includes wind shear, but also turbulence intensity and their variability, the sentence now reads as:

> The wind energy resource at a location is commonly assessed by estimating hub-height wind speed and direction, wind shear, turbulence intensity, and their variability (Murthy and Rahi, 2017) considering wind speed averaged over ten-minute intervals (e.g., Global Wind Atlas, Davis et al., 2023).

2. Line 22: "Turbulence affects the efficiency of wind turbine power generation resulting in fluctuating power output." This sentence is true, but might be misleading as written. Although not defined explicitly yet, we typically understand turbine 'efficiency' as the coefficient of power of the turbine. The primary way turbulence affects fluctuating power output is by changing the magnitude of the wind speed. The coefficient of power (efficiency) can also be affected by turbulence (e.g. [1, 2]) but this will usually be a much smaller impact than the effect of fluctuating wind speeds.

Text is rearranged so that the impact of turbulence on loads is discussed first followed by the discussion of the wind turbine power generation efficiency.

> In addition to the primary effect of wind speed variability, turbulence also impacts the efficiency of wind turbine power generation resulting in fluctuating power output (e.g., Elliot and Cadogan, 1990; Clifton and Wagner, 2014).

3. Line 23: "It also shortens their lifespan by inducing dynamic loads" References are needed for such a sweeping (and impactful) statement.

References are added:

> Turbulence negatively affects wind turbine lifespan by inducing dynamic loads (Leishman, 2002; Veers et al., 2023).

4. Line 59: "Rossby waves are a consequence of Earth's rotation (Rossby and Collaborators, 1985; Platzman, 1968), are embedded within global circulations." Typographical error

Typographical error was corrected, a superfluous "are" was removed.

5. Line 100: "The diurnal cycle is more pronounced over land than over water." While generally true, diurnal cycles can be significant in coastal environments.

The following sentence was added:

> While the diurnal cycle is more pronounced over land than over water in coastal environments it drives sea and land breezes.

6. Line 122: consider defining barotropic/baroclinic

The following sentences were added:

> In barotropic flows density, pressure, and temperature isosurfaces coincide. In contrast, in barotropic flows isosurfaces of density and pressure do not coincide.

7. Line 141: The authors could consider first introducing the flux Richardson number, which has a justified derivation from the TKE budget and is therefore a robust measure of stability, before introducing the gradient Richardson number which is its approximate form that is more practically useful. Then, more quantitative statements could be made than this: "It is generally accepted that the boundary layer flow is quasi-laminar when Rig exceeds unity."

We introduced the flux Richardson number and added the following text:

> The ABL stability results from interplay of turbulence production and suppression. As mentioned, while shear results in production of turbulence, buoyancy can be either a source or a sink of turbulence. A non-dimensional parameter that characterizes atmospheric stability is the flux Richardson number defined as a ratio of buoyancy to shear production of turbulence:
>
> $$Ri_f = \frac{\frac{g}{T_0}\overline{w'\theta'}}{\overline{u'w'}\frac{\partial \overline{u}}{\partial z} + \overline{v'w'}\frac{\partial \overline{v}}{\partial z}}$$
>
> Estimating atmospheric stability using the flux Richardson number requires flux measurements which are frequently not available. Generally, measurements of wind and temperature profiles are more readily available. An alternative non-dimensional stability parameter can be more practically estimated as a ratio of ~~As mentioned, atmospheric stability depends on wind shear (S) and static stability (N)~~ static stability (N) and wind shear (S).

8. Figure 5: The roughness sublayer, surface layer, and outer layers appear to not be defined in text or in the caption.

We have added the following sentence to the figure caption:

> A roughness sublayer is affected by surface roughness elements, surface layer is a layer throughout which turbulent fluxes of momentum, heat, moisture and other constituents are approximately constant, while the outer layer represents the rest of an ABL extending to the entrainment zone through which an ABL interacts with the upper troposphere.

9. Line 230: “There is a lack of measurement of the different ILS components.” Unclear what this sentence means, consider rephrasing

The subsection 3.5 was modified and now includes definition of integral length scales.

3.5 Integral Length Scales

The spatial dimensions of the most energetic eddies are commonly quantified by integral length scales (ILSs) ~~, L_k^i~~. The ILSs are commonly estimated using correlation functions. A spatial autocorrelation function for a turbulent quantity φ is defined as:

$$\rho_{\varphi\varphi}(\mathbf{x}, r\mathbf{e}_\alpha) = \frac{\overline{\varphi'(\mathbf{x})\varphi'(\mathbf{x}+r\mathbf{e}_\alpha)}}{\overline{\phi'(\mathbf{x})^2}}$$

Here, ρ is a spatial correlation function of a variable φ at point in space $\mathbf{x}$, r is a distance from $\mathbf{x}$ along the direction of the unit vector $\mathbf{e}_\alpha$, and the overline denotes the ensemble average. In case of spatially homogeneous flows the ensemble average can be replaced with the spatial average, while in case of statistically stationary flows it can be replaced with the time average. The ILS of a variable φ along the direction $\mathbf{e}$ is then defined as:

$$L_\varphi^\alpha = \int_0^\infty \rho_{\varphi\varphi}(\mathbf{x}, r\mathbf{e}_\alpha)dr$$

If we instead of the separation vector $r\mathbf{e}$ we introduce a time offset ϑ then we can compute the temporal autocorrelation and the corresponding integral time scale.

The unclear statement was clarified as follows:

> There is currently a lack of direct measurements of all autocorrelations required to estimate the individual ILS components which limits our understanding of the ABL structure.

10. Line 290: "In addition to the characterization of ABL flows motivated by wind energy, we add here a more mathematical discussion to explain the statistical content of the characterization." I did not follow what is meant exactly by this sentence (and therefore the motivation of the section). Consider rephrasing. More generally, this subsection contains important content but is written at a more advanced level than the earlier parts of the paper.

The subsections 3.7 and 3.8 were merged into the new subsection 3.6 "Statistical Hierarchy, Spectra, and ~~Cospectra~~ Coherence" and the introduction of statistical tools was rewritten. The first two paragraphs now read as follows:

3.6 Statistical Hierarchy, Spectra, and Coherence

The chaotic nature of turbulent flows makes flow variables suitable for analysis using statistical tools. The properties of fluctuations of an observed turbulent flow scalar quantity q can be represented by the probability density function (pdf) $p(q)$. If we consider a data set $\{q_i; i = 1, ..., N\}$, a pdf $p(q)$ is insensitive to any order in the sequence i (here i can denote a time or space index). Only if two values q_i and q_j, with $j = i + \Delta$, are statistically independent the characterization by the pdf $p(q)$ is complete. While a pdf of a flow quantity in a non-fluctuating laminar flow is represented by a delta function $p(q) = \delta(q - \overline{q})$, the pdf of a turbulent flow quantity determines all its statistical moments $\overline{q^n} = \int q^n \; p(q) \; dq$. Statistical analysis of a turbulent flow quantity is commonly focused on central moments computed with respect to the mean value $\overline{q}$, $\overline{\mu^n} = \int \mu^n \; p(\mu) \; d\mu$, where $\mu = q - \overline{q}$. The second moment or variance is $\sigma_\mu^2 = \overline{\mu^2}$. We can define a transformed variable $\tilde{q} = \frac{\mu}{\sigma_\mu}$ and then the associated pdf is $p(\tilde{q})$. In Fig. 7 (a) an example of $p(\tilde{q})$, where $\tilde{q} = u'$, is shown in which the pdf has pronounced heavy tails. The corresponding Gaussian pdf is completely defined by $\overline{u} = 0$ and σ_μ and displayed as a solid curve. Note the large difference of the probability of large events, a $\mu = 5\sigma$ event is more than 100 times more frequent in the empirical pdf than in a Gaussian distribution. Similarly, the pdf of normalized time increments, $\frac{\delta u}{\sigma_{\delta u}} = \frac{u(t+\Delta t) - u(t)}{\sigma_{\delta u}}$ of velocity has heavy tails Fig. 7 (b). Quantities characterized by such heavy-tailed pdfs are also called intermittent.

Since turbulent structures lead to dependencies of q_i and q_j, such dependencies or correlations are of interest. Statistically, this is captured by the joint-pdf $p(q_i, q_j) = p(q_i, q_{i+\Delta})$, which for homogeneous data depends only on the separation Δ. The lowest order moment of this joint-pdf is autocovariance $\overline{q_i\, q_j}$. The Wiener–Khintchine theorem states that the power spectrum $S_{qq}(n)$ is the Fourier transformation of autocovariance, where wave number or frequency, n, is proportional to $1/\Delta$. While a power spectrum characterizes energy content at different spatial or temporal scales, it does not characterize small-scale intermittency of turbulence. The intermittency is characterized by higher-order moments of increments $\overline{(q_{i+\Delta} - q_i)^n}$ (Frisch, 1995, for more details see also Morales et al., 2012). This statistical intermittency must be distinguished from the global intermittency induced by large coherent structures such are, for example, Kelvin-Helmholtz billows. The joint-pdf can be defined for two or more variables, the so-called multivariate statistics. The moments of different order of multivariate joint-pdfs are covariances. A covariance of two variables q_i, and r_j is denoted by $\overline{q_i r_j}$ and the corresponding Fourier transform is a complex function, the cross-spectrum $S_{qr} = C_{qr}(n) + iQ_{qr}(n)$, where the real part, $Co_{qr}(n)$ is the cospectrum and the imaginary part Qu_{rs} is the quadrature spectrum. The coherence function is defined as:

$$Coh_{qr}(n) = \frac{|S_{qr}(n)|^2}{S_{qq}(n) S_{rr}(n)}$$

11. Line 335: Typographical error

Corrected: Figure 10...

12. Section 4.1: The authors may add discussion regarding the quantitative identification of LLJs [e.g. 3]

The following text was added to the subsection 4.1:

Since Lettau and Davidson (1957) first identified LLJs during the Great Plains Project there were many attempts to unequivocally define an LLJ (e.g., Bonner, 1968; Whiteman et al., 1997; Banta et al., 2008), however this did not result in a generally accepted

> definition. Such a definition was elusive due to relative sparsity and resolution of observations. We need more coordinated measurement campaigns with instruments for both mesoscale and microscale flows. AWAKEN (Moriarty et al., 2024) is a field study that provides such observations. In recent analysis of a long-term observations of LLJs at the Atmospheric Radiation Measurement Southern Great Plains site Debnath et al. (2023) used the following criteria to detect LLJs: location of the wind speed maximum where the difference between the wind speed maximum and the wind speed at the top of the jet is at least 2 m/s and this difference exceeds 10 % of the maximum wind speed. They found that LLJ wind profile cannot be represented by the shear exponent only.
>
> Several attempts to analyze spectral features associated with LLJ structure and relate them to spectra observed in canonical stably-stratified ABLs without a jet (Kaimal, 1973) did not result in consistent findings. While Smedman et al. (2004) and Hallgren et al. (2022) found that low frequencies of the streamwise velocity spectra associated with LLJs are suppressed, however, these results are not consistent with some other studies (e.g., Duarte et al., 2012). The knowledge gained from the further analysis of these and other measurements that include characterization of mesoscale conditions is expected to shed light on how to couple the mesoscale and microscale modeling to fit LLJ's nature. ~~It should also be noted that the LLJ structure has not yet been consistently related to the spectral features described above.~~

Also, the following paragraph was moved to the end of the subsection 7.3.1 where it better addresses the gaps in characterization of LLJs:

> 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.

13. Section 4.4 and Section 5 have duplicated content on flow over complex terrain

The following redundant text was omitted:

> Turbulence characteristics in complex terrain are impacted by the wide range of flow phenomena in addition to spatial inhomogeneity frequently resulting in non-equilibrium conditions. As indicated above,...

and the following text was moved from the subsection 4.5 to the end of the section 8.5:

> There has been relatively little research into the interactions between downslope wind storms, power production, and turbine loads compared to studies of other extreme wind events. Observational studies, such as those by Sherry and Rival (2015), studied wind ramps associated with Chinook winds downwind in the Canadian Rockies. One of their findings was that turbulence intensity was generally large during ramp events. Kozmar and Grisogono (2020) provided a review of characteristics of downslope wind storms including mountain wave overturning and quasi periodic oscillations in wind speed and elevate turbulence levels result of Kelvin-Helmholtz instabilities that are particularly relevant for wind energy applications. They point out the need for updating engineering standards to account for large wind velocity fluctuations associated with downslope wind storms.

Please notice that the subsection 4.5 addresses downslope wind storm phenomena, while the section 5 addresses observations related to wind energy.

14. Line 465: I am unclear what the authors mean when they say that computing turbulent fluxes requires Taylor's hypothesis

The sentence was replaced with the following one:

> By assuming that turbulence is frozen in time as it advects by a sensor, i.e. using Taylor's hypothesis (c.f., Wyngaard, 2010), one can use high-rate time series of measurements at a point in space and interpret them as a spatial record.

15. Line 567: "Ideally, assuming a steady laminar flow, the power produced in this region is given theoretically by:" – "Ideally, assuming a steady laminar uniform flow, the power produced in this region is given theoretically by:"

The text was modified as suggested by the reviewer:

> Ideally, assuming a steady laminar uniform flow, the power produced in this region is given theoretically by:

16. Line 592: Of relevance: recent evidence suggests the rotor equivalent wind speed model does not fully capture the effects of the wind profile shape (i.e. wind shear and veer), [4. 5]

The following sentences and references suggested by the reviewer were added:

> In addition to wind shear, wind veer also impacts power production (Mata et al., 2024). Vratsinis et al. (2025) analyzed performance of a large offshore wind farm and concluded that the IEC-defined rotor equivalent wind speed does not represent the full effects of shear and veer on a large offshore wind turbine.

17. Section 7.1: Given the focus of this review paper on turbulence, and the discussion of wind tunnel tests, the authors should consider confronting the issue of dynamic similarity, especially Reynolds number, and how that affects the interpretation of wind tunnel tests [6, 7]

The following text was added to the end of the subsection 7.1:

> While these wind tunnel studies were characterized by Reynolds numbers several orders of magnitude lower than those characteristic for conditions under which utility-scale turbines operate, Miller et al. (2018, 2019) used a high-pressure wind tunnel to achieve dynamic similarity to study both vertical and horizontal axis wind turbine power performance. Conducting experiments at a range of rotor diameter based Reynolds numbers they have shown that the scale effects can significantly impact horizontal axis turbine performance. However, they observed Reynolds number invariance of the power coefficient as a function of tip speed ratio for a cord-length based Reynolds number greater than 3.5×10^6 for a horizontal axis wind turbine and 1.5×10^6 for a vertical axis wind turbine.

18. Section 7.3.1: Motivation is given via Great Plains, but LLJs can also be quite important in coastal regions for offshore wind [8]

In subsection 7.3.1 the impact of LLJs on wind power is discussed, therefore the de Jong et al. (2024) reference better fits in subsection 4.1 where coastal LLJs are discussed. We have therefore added de Jong et al. (2024) reference to subsection 4.1. In the subsection 4.1 we have also added Olsen et al. (2024) reference that addresses North Sea and Baltic LLJs.

19. Line 725: This discussion of the scale of wind turbines and farms could be

relocated to the introduction

TBD: The discussion was moved to the Introduction, where the following text was added:

> For example, offshore, where the size limits have not been reached yet, wind turbines are approaching 300 meters (e.g., the Haliade-X turbine, 260 m, or the Vestas V236-15.0 MW, 280 m), beyond the frequently shallow marine ABL. Furthermore, modern wind farm clusters are expanding to areas of thousands square kilometers (e.g., Hornsea area 7240 km^2, Minnesota wind farms about 5000 km^2) spanning a wide range of atmospheric scales.

20. Line 765: Reference formatting

Reference formatting was corrected.

21. Line 923: Typographical error

Typographical error was corrected.

22. Section 8.1 is comprehensive and well-written. Related to the discussion in paragraph starting at Line 935: There has been recent discussion as to whether failure rates may be increasing, and high profile failure events in the past several years are gaining more attention. The authors may consider a brief summary of knowledge gaps that could be related to these failures. Growing turbine size and veer are mentioned already. Aeroelasticity and the coupling between SIV/VIV and anisotropic/intermittent ABL turbulence are pertinent.

Following reviewer's suggestion the following paragraph was added to the subsection 8.1

> Flow conditions, characterized by anisotropic, intermittent turbulence result in dynamic instability leading to flow-induced vibrations and blade flutter causing unsteady aerodynamic forces. Dimitrov et al. (2017) quantified the impact of turbulence length scales and anisotropy associated with normal and extreme turbulence on fatigue and extreme loads. They concluded that compared to the observed standard deviation of turbulence in the IEC 61400-1 Ed.3 standard is underestimated. Perturbations due to turbulence can result in large vortex-induced vibrations (Grinderslev et al., 2022).

> As the size of wind turbines increases the impact of vortex-induced vibrations (Grinderslev et al., 2023).Naqash and Alam (2025) provide a review of impact of flow-induced vibrations on turbine blade loads, fatigue, and failures.

23. Line 974: Reference formatting

Reference formatting was corrected.

24. Line 981: More recent and relevant publication [9]

The following text and the reference were added:

> Studying yaw control for a wind turbine and a wind farm, Damiani et al. (2018) concluded that turbulence intensity is one of the primary causes of damage equivalent loads.

25. Line 981: "Furthermore, they state that turbulence length scales are smaller in complex terrain, which is why turbine fatigue loads tend to be higher in complex terrain." I imagine it would be challenging to make such a general statement, especially in light of the discussion earlier on AGW and the lack of a unified standard on what is "complex terrain"

The sentence was modified to more accurately represent the finding in Riziotis and Voutsinas (2000):

> Furthermore, they state that the higher turbulence intensity is the main cause of higher turbine fatigue loads in complex terrain.

26. Line 992: "Englberger et al. (2020) used LES to study what controls downwind wake deflection and found the blade rotation when combined with directional shear (wind veer or backing) resulted in a significant wake deflection." This is a good reference but seems out of place in a section about fatigue loads. There are many more studies on how ABL phenomena and turbine operation (shear, stability, Coriolis effects, yaw, ...) affect wakes in general, beyond blade rotation+shear. More generally, this review does not describe wakes/farm scale processes, so this reference is somewhat isolated.

Following reviewers suggestion the sentence and accompanying reference were removed.

> Englberger et al. (2020) used LES to study what controls downwind wake deflection and found the blade rotation when combined with directional shear (wind veer or backing) result in a significant wake deflection.

Since we do not focus on wake induced turbulence, we have also removed the following sentence referencing wake-wake interactions

> Given that the impact of turbine loading is highly non-linear, additional fundamental insight into wake-wake interactions is required to improve predictions of the turbulence conditions inside extended wind farms or the interaction between wind farms.

27. Figure 15: Unclear what Steps 1, 2, and 3 are

The following sentence was added to the caption of Figure 15

> Steps 1 through 3 represent modifications of the inflow by varying wind shear (STEP 1), veer (STEP 2), and turbulence level (STEP 3).

28. Line 1030: This paragraph has high overlap with the previous section on ABL turbulence models

The paragraph was moved to the section 6 "Modeling of ABL Flows" which now includes the following text:

> TurbSim (Kelley and Jonkman, 2007) is one of the most commonly used ~~currently a~~ tools that can rapidly generate a range of idealized turbulent fields. To meet the new design needs, TurbSim must be extended to provide a wider range of realistic turbine inflows. Turbulent inflow can also be generated using LES; however, such simulations are computationally expensive. Therefore, there is still a need for a faster alternative. In addition to a tool like TurbSim, recent developments in Artificial Intelligence and Machine Learning (AI/ML), in particular state-of-the-art physics-informed deep learning approaches, provide an opportunity to develop ML models using vision transformers that could generate realistic turbulent fields at a fraction of a cost of an LES (e.g., Stengel et al., 2020; Dettling et al., 2025). Alternatively, coupled simulations could be used to create a public database of ABL flows, similar to the Johns Hopkins

> Turbulence Database (Johns Hopkins University, 2021; Zhu et al., 2025).
>
> As larger modern turbines are exposed to a wider range of atmospheric conditions, there is a need to better represent the turbulent inflow that impacts their performance. To resolve ABL turbulence, from the largest boundary layer eddies into the inertial range of turbulence characterized by Kolmogorov -5/3 spectrum (Kolmogorov, 1941), we can employ large-eddy simulations (LESs).

29. Section 8.3: Relevant to the discussion on 1059, recent LES indicates that wake added turbulence depends on ABL stability [10] which is not well addressed by existing empirical models

Considering the reviewer's recommendation that the manuscript focus on the impact of atmospheric turbulence on the first row of turbines, and given that other papers in the series address wake-generated turbulence and its impacts, we have decided to remove the subsection 8.3 from the manuscript.

30. Line 1089: "however, the disadvantage is that the high Reynolds number characteristic for atmospheric flows is not possible to achieve" This statement is not strictly correct, as demonstrated in Refs. [6, 7]. Also, shear and stability is possible to achieve [e.g. 11, 12], but veer, LLJs, and AGWs are certainly more challenging.

The statement was corrected as suggested and the reference added and it now reads as follows:

> While there are studies that replicated some of the atmospheric conditions (e.g., Chamorro and Porté-Agel, 2010), the disadvantage is that unless a wind tunnel is pressurized (Miller et al., 2019), it is not possible to achieve the high Reynolds number characteristic for atmospheric flows. In addition, a range of atmospheric stabilities and Coriolis effects and their consequences (e.g., veer, LLJs, AGWs) are difficult or impossible to replicate.

31. Line 1123: "Turbine incidents and failures are underreported due to legal and other proprietary considerations." Strong statement that may be true, but would require references/proof to include in this paper

Instead of the quoted sentence the following text and a reference were added at the end of 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 for better assessment of the impact of extreme events on individual wind turbines and wind farms and for more accurate risk assessment.

32. Line 1151: The sentence is incomplete/cutoff

The sentence was completed as follows:

While this enables a level of confidence in the statistical prediction of extreme wind for wind turbine design, considering the potential impact, the standard should be continuously evaluated based on available observations and high-resolution simulations.

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