Impacts of the Low-Level Jet's Negative Wind Shear on the Wind Turbine

Walter Gutierrez, Arquimedes Ruiz-Columbie, Murat Tutkun, and Luciano Castillo

Response to Referee # 2

We are thankful to the referee for his comments that significantly improved the quality of our manuscript. Responses are indicated below and proper changes are highlighted in the new version of the manuscript.

Major comments:

1) **Referee comment:** Alltogether, the manuscript is lengthy. The authors should consider to identify the key cases and results and concentrate on these. Also the literature review, while much appreciated, appears to be more extensive than necessary.

   Author's response: We highly appreciate the referee for the recommendation, which contribute to make the manuscript more concise.

   Autor's changes: "Literature Review" has been merged with "Introduction" into a single section named "Introduction". The former subsection "Data collection methods" has been renamed "Previous experiences on data collection". Overall, the number of references has been significantly reduced. Finally, the last paragraph of the former section "Introduction" has been modified to update the section numbers of the cross-references. On the other hand, the explanation of the PDF (in former section 4.1) has been compacted.

2) **Referee comment:** The manuscript reads quite technical and should be improved in terms of a dedicated research question and a rigorous sequence of steps and arguments to give answers to that question. Most of the necessary elements are already mentioned in the paper, but they should be better worked out. The research question is actually indicated in the introduction, P2L17. However, the introduction does not lead the reader to this question, nor is a sequence of investigative steps directly developed from it.

   Author's response: The authors thanks the referee for the recommendation, which undoubtedly increase the interest on the manuscript.

   Autor's changes: The final paragraphs of the "Introduction" have been modified to highlight the importance of the research question. Two paragraphs are now devoted to the reasoning leading to the research question, from " In some parts of the world such as Europe, wind turbines…" to "… or mitigates those effects."

   Thereafter, the sequence of investigative steps has been introduced as follows: " To answer this question, a process has been devised to find out how the turbines responses vary with the presence of negative wind shears. First, enough wind information was collected to allow the quest of typical LLJ's incidents. Second, a parameter was devised as independent variable that quantify the proportion of rotor area that receives negative shears. Then, cases were generated by gradually modifying the parameter. Finally, simulations of the turbine responses were performed for each case and the results were compared to draw conclusions."

3) **Referee comment:** On P7L7-8 the generation of the necessary 2D wind fields evolving in time from raw met tower measurement data is only indicated but not sufficiently explained. As this is a central step in data processing where assumptions and simplifications have to be applied, a more detailed description is necessary.

   Author's response: The authors thanks the reviewer for this insightful observation that clearly definitely makes clearer to the reader the procedures used.

   Autor's changes: The following text has been added immediately thereafter: "One decision to make was how to construct a 3D box of wind speed information. The tower is a line of measurements which provides one dimension in the vertical axis. The series of collected data generate the second dimension in the streamwise axis. Finally, an assumption must be made to generate the third dimension in the spanwise axis and complete the 3D model. Data from the tower reveal that LLJs are very stable phenomena in terms of wind speed and direction, both of which vary very slowly with time. Moreover, the LLJ's horizontal scales are large, both along and across the wind direction. These two observations support the expectation that horizontal rotational motions are mostly insignificant within LLJs winds and therefore, that the wind speed vector would be quite similar in the spanwise vicinity of the tower. The third dimension in the spanwise axis was thus obtained by replicating the measurements obtained at the tower at the same height."

4) **Referee comment:** On P7L31-32 it is explained that simulations were performed using the NREL Wind- PACT 1.5MW WT. Compared to the current state of technology, this is a rather small machine. It seems that at least the NREL 5MW WT would have been more appropriate, especially considering the focus of the manuscript on future, very large and tall WTs. Please comment on this and justify the WT model selection.

   Author's response: The authors agree that there exists a loose trend of having larger wind turbines at greater altitudes. The tendency nonetheless not always holds; for example, the current world's tallest wind turbine is a Nordex 3.3 MW that reach 230 m but has only a capacity of 3.3 MW. The turbine surpassed the height of the previous tallest one, the Vestas V164, by around 10 m, even as the latest is more than 2.5 times as powerful (8 MW).

   For our simulations, we needed to select a single wind turbine that could fit a broad range of altitudes, from less than 100 m to almost 200 m (measured from the ground up to the height of the tip of the blade in the upper position). The reason is that we have been studying and comparing the impacts of the LLJ in many situations, starting with the peak of the jet occurring much higher than the turbine rotor and ending with the jet peak impacting below the rotor. We needed to ensure that the turbine model was the same to ensure a fair comparison among the cases.

To select a wind turbine model, not only the hub height was important, but also the rotor radius, in order to keep the rotor within the altitude constraints for all simulations. First, a blade tip in the upper position should never reach 200 m (the limit of the wind measurements from the tower) even when testing cases with the jet peak impacting below the turbine rotor. Second, a blade tip in the lower position should never approach the ground even when testing cases with the jet peak impacting above the turbine rotor. With a rotor diameter of just 70 m, the NREL Wind- PACT 1.5MW WT is perfect to fit in all simulation cases. As a contrast, the NREL Wind- PACT 5MW WT has a rotor radius of 128 m, which makes almost impossible to comply with the constraints for all cases.

5) **Referee comment:** The results indicate reduced loads and deflection amplitudes for several WT components in case of an LLJ. These improvements should be made quantitative in some meaningful way and presented, e.g., in a table, probably only for selected cases. Thus an impression of their relevance would be given.

   Author's response: The authors thanks the reviewer for this recommendation. Careful consideration was given as to how summarize results in a table. However, there is no simple parameter that can synthetize the information in the graphs. For example, several statistical parameters are visualized directly or indirectly: means, medians, percentiles, skewness, etc. and each of them only tells part of the story. As in many cases, the graphs are compelling in putting together all massive information to make evident to the reader in a glimpse the salient points.

   The information is shown in terms of variations with ξ. Consolidation of variables (e.g. the maximum of the medians, etc.) may be attempted; however, they would provide limited information compared to visualizing the trends across all values of ξ.

Specific comments:

1) **Referee comment:** Fig. 1 could probably be canceled. Its information contents is minimal and mostly repeated in Fig. 2, if the caption is adapted accordingly.

   Author's response: The authors thank the referee for the recommendation.

   Autor's changes: Figure 1 has been removed and the following text has been added immediately after the definition of ξ: "The parameter ξ is a continuous variable. Some characteristics values are of interest. First, if $\xi = 1$ then the peak of the jet impacted exactly at the altitude of the lowest point of the turbine's sweep area and thus the wind shear was entirely negative across the turbine's rotor. Second, if $\xi = 0$ then the peak of the jet occurred exactly at the height of the turbine's hub and thus the wind shear was positive below the hub and negative above. Finally, if $\xi = 1$ then the peak of the jet impacted exactly at the altitude of the highest point of the turbine's sweep area and thus the wind shear was entirely positive across the turbine's rotor."

2) **Referee comment:** Notation: The vertical axes in Figs. 3-10 are labeled (z-z_0)/R while the captions mention "Variation with nxi", and Eq. (3) defines nxi slightly different from the figures. Please clarify and use nxi consistently throughout the manuscript, avoiding confusion of the reader. For the same reason also use the symbol nxi in axis labelling of the figures if appropriate.

   Author's response: The authors thank the referee for noticing the mismatch.

   Autor's changes: The y-axes labels have been changed to the variable name.

3) **Referee comment:** In the conclusions, P18L6, the term "torque" should be explained more precisely. Torque on which component(s) and with respect to which axis.

   Author's response: The authors thanks the reviewer for the recommendation to clarify the term.

   Autor's changes: The sentence has been rephrased as follows: "Therefore, the magnitude of the torque created by the negative shear upon the long elements (such as the blades and the tower), especially around the spanwise axis, becomes smaller than the one created by the positive shear."