Response to Referee 1

Periods of constant wind speed: How long do they last in the atmospheric boundary layer?

Referee's comment (RC) in blue
Author's comment (AC) in black

In gray-italic: text from the revised version of the manuscript.

AUTHORS:
Dear Referee, thank you for highlighting the importance of our research. We appreciate your feedback. In the following, we would like to address the open questions and comments you have posted.

We use the following abbreviations: Constant wind speed (CWS), Period of constant wind speed (T_c), Atmospheric Boundary Layer (ABL), Wind turbine (WT), Probability Density Functions (PDFs).

GENERAL COMMENTS

REFEREE:
The paper is strong in the technical aspects with well selected analyses to possibly support the hypothesis that the distribution of the CWS event durations can be described with an exponent.

While it is an interesting topic to address, and important to highlight that the standard turbulence model is inadequate, the paper lacks proper motivation. More information would be needed to determine how these events may increase the WT loads. Are they coherent, i.e. do they occur throughout the heights enveloping the rotor area? Which design case of the IEC WT design standard do they fit into, or is a new design case needed (Introduction, L31)? How can the knowledge of these events help the WT and wind plant controller? Can an event be predicted from past few seconds of data?

A major shortcoming is that the period of the observation used for the analysis is too short. Much more data must be analyzed for a meaningful publication. One could, for example, object against using the statement "conclusive", not once but twice: in the Abstract, and in the section 4.2, page 11. When the period of data collection is extended, the data could then also be separated by wind direction, surface heat flux, and possibly expose additional properties.

The curvature of the spectrum (figures 5, 6, 7) indicates imperfect power law. There is curvature present even at the long durations, which does not help the results being conclusive. One would need to propose a theory at least trying to explain the power-law with physical characteristics of the boundary layer (stability, surface roughness, ...) and then blame the disagreement on incomplete data or another possible cause.

AUTHORS:
Based on your comment that the motivation of our research was insufficiently stated, we have revised, rearranged and incorporated additional statements in the Introduction (Sec. 1) to reinforce the significance of our study. In the new version of the manuscript, we contextualize in a more clear way, compared to the original version, the periods of CWS within the general characterization of turbulence. We also explicitly explain the potential relevance of periods of CWS for WT loads.

Starting in L.35, we motivate our research within the framework of general characteristics of turbulent flows.

From L.60 to L.69 we better formulate our hypothesis regarding the possible increased loads on a WT induced by a period of CWS with certain characteristics. This can be the case when a localized period of CWS occurs on a limited area on the rotor plane.

You have commented on the coherence as a relevant feature of the CWS periods for assessing their potential impact on WTs. Indeed, we have investigated coherent CWS events through the analysis of the FINO1 wind measurements at different heights (see details of the data in Sec. 2.2 of the manuscript). The results of our preliminary investigations suggest that the periods of CWS appear localized at different heights. An example of the analyses is shown in Fig. 1 in this document. Nonetheless, further studies from meteorological mast arrays (e.g., GROWIAN data or the WiValdi test site) should shed more light on the spatial coherence of these events.

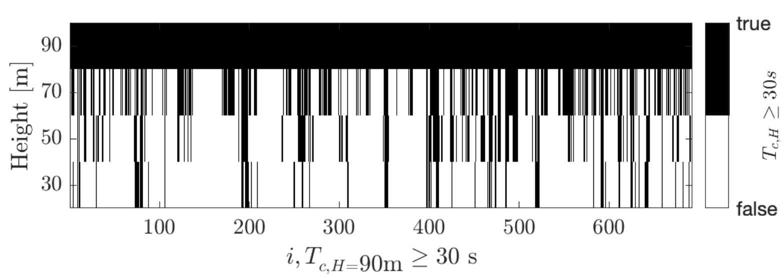

Figure 1: Events $T_c > T_{min}$ at different heights, conditioned on $\tilde{H} = 90$m. First, the conditioning height $\tilde{H}$ is defined. Next, for each i event $T_{c,i} > T_{min}$ at $H = \tilde{H}$, the occurrence of T_c at the remaining heights H=[70, 50, 30]m is evaluated. Black lines depict the occurrence of an event. Note that T_c at all heights are conditioned so that $T_c > T_{min}$. For the example in this figure, $T_{min} = 30$s and $\tilde{H} = 90$m.
In this case, 37% of the events at 90m are happening simultaneously at 70m. This number decreases to 11% when comparing the periods of CWS between 90m and 30m. The same evaluation for coherent events has been performed conditioned by different values of T_{min} and reference heights $\tilde{H}$.

We have referred to our preliminary investigation on the coherence of periods of CWS in L.299 in the Outlook of the manuscript:

Accordingly, preliminary investigations (detailed in Appendix G) suggest that the periods of CWS show a tendency to be localized at different measurement heights, and therefore, may become of particular interest for turbines with larger diameters.

Additionally, we now have provided details about the coherence investigation in the Appendix G: "Spatial coherence of T_c" of the manuscript, including Fig. 1 shown above.

Concerning the issue of the insufficient length of the investigated period, we agree that the period of 4.6 days for the analysis in the original manuscript might have been too short. Therefore, we re-analyzed for a longer period (roughly one year; see the revised version of the manuscript). Our major finding, i.e., the power-law behavior of the tails of the probability density function (PDF) of the CWS periods, is confirmed with even more accuracy. The apparent curvature in the original log-log-plot of the PDFs decreased as well, which led to more accurate power law fits (see Figs. 3 and 4 in the manuscript).

Regarding a potential theoretical explanation for curvature effects in the power laws, we must emphasize that our findings here are entirely empirical, and future work has to be devoted to describing such periods of CWS in the ABL within a coherent statistical description.

L.301 in the Outlook refers to the need of a complete description of the CWS periods:

Future work has to be devoted to assessing the relevance of the empirically observed power-law behavior of periods of CWS on turbine loading. For that, the complete statistical parametrization of periods of CWS, in both time and spatial domains, should be assessed and improved(...).

You have posed an interesting question about a potential IEC Design Load Case (DLC). To our knowledge, there is currently no DLC that addresses non-coherent spatial conditions during the operation of the turbine. We agree that considering a standardized framework for the load assessment of the loads under such turbulent conditions would be highly relevant for the turbine design and certification processes. However, before adding such a feature to the IEC design guidelines, intensive load analyses with a specific WT model and control strategies have to be performed together with industrial partners.

SPECIFIC COMMENTS

Abstract

L3: please elaborate on "particular dynanmic responses"

With "particular dynamic responses" we refer to unexpected responses (e.g. loads, deflections, resonances) induced by periods of CWS with specific characteristics. An explanation of our hypothesis is given in L.63-L.65:

A more entangled case might occur when resonant or near-resonant dynamics appear for specific periods of CWS, over which the resonance can be strongly excited. In particular for the larger WTs, the CWS periods may be restricted to a sub-area of the rotor plane. In this case, resonant dynamics exhibiting 3P oscillations may be amplified.

L6: what is meant by "the challenging power law behaviour" and why is this introduced with a reference to extreme events? Extreme events are not mentioned anywhere in the paper, other than extremely long CWS duration. Speaking of extreme events ... please verify if they perhaps follow any of the typical extreme event distributions

Thank you for this important comment. We admit that the term "challenging power law behavior" might have been misleading. We intended to discuss the divergence of moments of certain orders dependent on the power law's exponent in the Pareto distribution. The Pareto distribution belongs to the class of heavy-tailed distributions. Regarding the reference to extreme events, we refer to extreme events in the sense of very long periods of CWS, which is the focus of our investigation.

We would also like to thank you for your suggestion regarding considering typical extreme-value PDFs. However, in our study, we investigate the statistics of all measured periods T_c and analyze the resulting tails of their PDFs. By doing so, we clearly observe extreme events but do not follow explicitly the procedure of extreme value statistics (i.e., for T_c larger than a threshold). In that way, extreme value distributions can not be applied.

As our new results based on a much longer data set suggest power law exponents rather far from the mentioned criticality, we no longer consider this aspect significant for the manuscript. Therefore, we removed L.6 in the original version of the manuscript.

We included L.55-L.59 for describing the peculiarity of the power law behavior:

A characteristic feature of a power law distribution is the absence of an intrinsic scale, i.e., the probability of observing a realization larger than ξT is $\xi^{-\alpha+1}$ times the probability of observing a realization larger than T; independently of the value of T. The far-tail regime of many distributions occurring in complex systems is assumed to exhibit power-law behavior [Laherrere and Sornette, 1998]. In the context of wind energy, for instance, a Pareto distribution has been tested to extrapolate the response of a multi-megawatt wind turbine generator [Dimitrov, 2016].

Section 2.1

L109: It is hard to imagine how would a WT know that a CWS event is imminent and switch into the appropriate control mode in practice.

Thank you for your question. We admit we do not have a concrete answer to how the control strategy would be in an imminent period of CWS. In L.126 (L.109 in the previous version) we refer to the control practices of the WT for introducing a reference value for defining the factor A in $\varepsilon = A \cdot \sigma_u$ for measuring the periods of CWS within the characterization of the turbulent wind. Our intention is not to comment on or propose a reference parameter for identifying and reacting to a CWS structure in the context of WT control protocols. However, as a side remark, we believe that forecasting periods of CWS is not strictly necessary. Instead, the control system should be designed to react to long-lasting undamping events, which might be the effect of a period of CWS on the WT.

Section 3.4

L158: Good that the effect of the threshold amplitude is analyzed. Would it not be appropriate to add the resulting alpha exponent as another row in Table 3 and so enable easy comparison of different alphas

The results of α have been included in Table 3. Thank you for the suggestion.

A new version of the manuscript is provided along with a diff file.

References

N. Dimitrov. Comparative analysis of methods for modelling the short-term probability distribution of extreme wind turbine loads. *Wind Energy*, 19(4): 717–737, 2016.

J. Laherrere and D. Sornette. Stretched exponential distributions in nature and economy: "fat tails" with characteristic scales. *The European Physical Journal B-Condensed Matter and Complex Systems*, 2:525–539, 1998.