Response to Referee 2

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 your comments and recommendations. In the following, we would like to answer the points you have addressed.

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

This work addresses an academically interesting subject, but in its current form the draft unfortunately has some serious deficiencies. This includes speculation about extreme winds and turbine loads; the manuscript does not connect (directly) to extremes nor give a solid basis for loads. More importantly perhaps, its analysis of only 4.6 days of measurements cannot be used to justify statistics for loads accruing over the multi-decadal lifetime of a turbine, especially for extremes (see e.g. Dimitrov et al., 2018). The large variations in "critical" exponent for calm-durations may be a affected by this, but it is not clear. The lack of citation (or even use) of previous mathematical developments for persistence statistics is also an issue, especially given the conclusions about $T_c(\varepsilon)$; e.g., Hurst exponents (or even fractal dimension) for such have been explored by numerous authors. The fitting of a power-law over ranges where log-log plots show significant curvature, as well as the subsequent neglect of both the range of application or functionally different form of PDF – and implied lack of convergence for the power-law given the resultant exponents – are serious issues to be rectified, requiring more analysis. Overall the work on systematically quantifying the duration of 'persistent' periods offshore (and possibly capturing their statistics via a CTRW or other model) is interesting, and could merit publication; but to connect this with extremes would likely require significantly more work, which would be the subject of another separate publication(s).

We agree with the referee that the analysis period of roughly five days for the constant wind speed (CWS) events might have been too short. Therefore, in the revised version of the manuscript, we chose a more extended analysis period of roughly a year. This extension clearly supports our main findings, i.e., the existence of power-law behavior for the probability density function of the periods of CWS.

Furthermore, we must stress that "extremes" in the manuscript refer to comparatively long periods of quiescent wind speeds, i.e., the opposite of extreme wind field fluctuations. Nonetheless, we agree that the relation between such periods of CWS and their potential effect on turbine loading could be more precise. Therefore, starting on L.60 in the Introduction, we formulate in a more comprehensible way, our hypothesis regarding the possible increased loads on a WT induced by a period of CWS with certain characteristics. In particular, a relation to turbulent-non turbulent transitions [Neuhaus et al., 2024, Lobo et al., 2023] within the operation of the WT is mentioned. This can be the case when a localized period of CWS occurs on a limited area on the rotor plane. In Appendix G we provide evidence of such localized events. Starting in L.297 in the Conclusions, we discuss again the potential effect of periods of CWS on particularly large WTs.

We want to emphasize that we appreciate the referee's comments on the persistence events (excursions and zero-crossings). We include several references to these in our manuscript (see Introduction). However, even though persistent events such as inter-arrival times of excursions and/or zero-crossings, and our definition of periods of CWS exhibit certain similarities, they are not the same (please refer to Fig. 1 in this document and our response to your comment on l.1 in the SPECIFIC COMMENTS section).

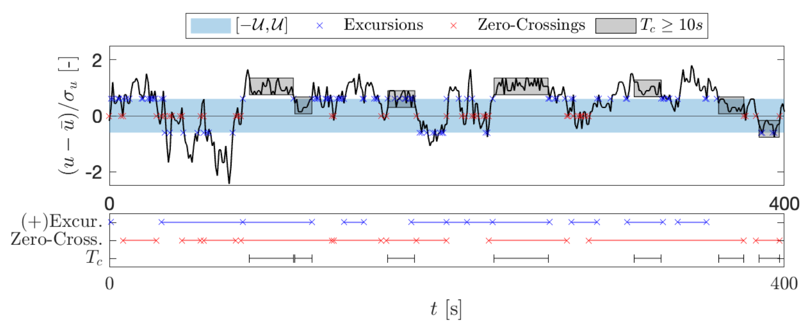

Figure 1: Illustration of excursions, zero crossings, and periods of CWS (T_c). In the top-plot, the exemplary wind speed time series are normalized to zero mean and standard deviation 1. The blue area defines the thresholds $\pm\mathcal{U}$ for considering the excursions, represented by blue crosses. $\mathcal{U}$ is defined as 2ε. The red crosses depict the zero crossings. The grey rectangles show the periods $T_c \geq 10s$ measured with $\varepsilon = 0.3$. The blue and red lines in the bottom plot depict the resulting inter-arrival times for the excursion measured at $+\mathcal{U}$, and the zero-crossings, respectively. For comparison, the periods $T_c > 10s$ are replotted as black lines. The inter-arrival times for the excursions and zero-crossings in the plot are filtered to be longer than 10s, as are the periods T_c.

To our knowledge, the analysis of periods of CWS in atmospheric turbulence and the obtained power law behavior of their PDFs has not been investigated before.

Furthermore, based on your suggestion of analyzing a more extended period of roughly a year of FINO data, the issue of potential curvature in the log-log plots of the PDFs shown in the original manuscript could be resolved.

Our reasoning for including a discussion of a wind field model (in this case, the CTRW model) in this context of periods of CWS is the following: Fig. 7 of the revised manuscript shows that the IEC Kaimal wind field model significantly underestimates the occurrence of long periods of CWS from atmospheric wind. For a future assessment of the relevance of periods of CWS for wind turbine loads, however, a wind field model that could reproduce the empirically observed power law behavior is indispensable. Therefore, we believe that Sec. 4.2 in the manuscript complements our findings in Sec. 4.1 quite well.

SPECIFIC COMMENTS

l.1: this is not a "non-investigated" topic; see e.g. Majumdar's "Persistence in nonequilibrium systems" (1999), or in the ABL, e.g. Chowdhuri, et al. (2020), https://doi.org/10.1063/5.0013911.
Thank you for recommending the literature. Persistence events including inter-arrival times between excursions and zero-crossing analyses have been investigated and reported in the literature. In fact, in the Introduction of the original version of the manuscript we have already referred to the zero-crossings analysis. Now we also refer to the concept of excursions.

However, even though their definition may be similar with respect to the periods of CWS, they are not directly related. Please see Fig. 1. In the top-plot, the zero-crossings of the zero-mean and normalized time series of $(u(t)-\bar{u})/\sigma_u$ are shown by red crosses. In [Chowdhuri et al., 2020], persistence is defined as the inter-arrival times between the zero-crossings. Comparatively, the grey rectangles mark the measured periods of CWS ($T_c > 10$s). For a clearer comparison, the bottom-plot shows the duration of the inter-arrival times between the zero-crossings (red lines). As observed, persistence events and periods of CWS are not the same. A period of CWS might enclose several zero-crossings, as well as several periods of CWS might be embedded inside an individual inter-arrival between zero-crossings.

Starting in L.35 in the Introduction, we now rigorously provide a context for the periods of CWS within the general characterization of turbulence. We introduce related concepts such as persistence, extreme winds and zero-crossings.

We emphasize the difference between persistence events (excursions and zero crossings), and periods of CWS in the Introduction L.49-L.52 of the manuscript:

It is worth noting that even though the inter-arrival times of both, excursions and zero-crossings, refer to structures between particular turbulent states, they do not correspond to the periods of reduced turbulent amplitudes, in which we are interested. Further details of the differences between CWS periods and inter-arrival *times between excursions and zero-crossings are shown in Appendix A*

We have now included the Appendix A: "Periods T_c vs persistence events" in the manuscript. There we incorporate Fig. 1 shown above in this document.

We have included the reference to [Chowdhuri et al., 2020] in the Introduction.

l.3: jets are not shown here to be "characteristic wind field structures" responsible for or related to constant wind speed periods, nor has this been referenced (shown elsewhere).
Here, we have used the term "jets" as an illustration for the reader rather than as a specifically defined phenomenon.

l.5: how have the constant-wind speed periods been related to extreme events? This should be removed unless such connection has been shown.
Please refer to our response to your GENERAL COMMENTS. In the second paragraph we stress that by "extreme events", we mean very long periods of CWS.

l.6-7: extreme events are known to follow "fat-tail" or power-law behavior, this is not new; "show" should be "confirm".

Thank you for this suggestion. We changed "show" to "confirm" in L.6 in the abstract.

l.45: wasn't the event-measurement approach developed in 2022, or how is this different?

It is true that a precursor of the approach was introduced in [Moreno et al., 2022]. We have actually removed this sentence from the manuscript. Our preliminary work ([Moreno et al., 2022]) is now disclosed in L.80:

In a preliminary investigation [Moreno et al., 2022], the method for the assessment of such events from wind speed time series was presented and first results on the characterization of the periods of CWS in terms of their duration and probability distributions were also reported.

Additionally, in L.122 we mention the difference, compared to [Moreno et al., 2022], of the method for measuring the events T_c from time series of the wind $u(t)$.

To introduce a systematic approach, in this paper ε is defined to be proportional to the standard deviation of the wind speed σ_u. Then, ε for fixing (...)

l.65: "Such strong periods are expected to have a stronger influence on a WT" does not seem correct, given that the periods with weakest fluctuations will have less effect on wind turbine loads.

Yes, we agree this is a misleading statement. We have removed it from the manuscript. Thank you for the comment.

l.81-82: note that this (and Fig.1) is essentially the (reverse of) the generalized gust description of L.Kristensen et al (1991) following from Rice (1945).

Thank you again for calling attention to these important studies regarding extreme wind speeds and the waiting times between them. However, as stated in our response to your GENERAL COMMENTS, we do not address extreme winds but extreme (very large) periods of CWS. Even though the inter-arrival times between extreme winds (or gusts) seem similar to the periods of CWS, they do not refer to the same wind structure. Please see again to Fig. 1 in this document.

In the top-plot of Fig. 1, the blue area defines the thresholds $\pm\mathcal{U}$ for considering the extreme winds (also called gusts, or excursions). The blue crosses depict the times when such thresholds are crossed. Again, periods of CWS (T_c) larger than 10s are marked by the grey rectangles. For comparison, the threshold $\mathcal{U}$ for the excursions is defined as twice the threshold ε. In that way, a period T_c inside $\pm\varepsilon$ would contain the size of the fluctuations defined inside the ranges $(0, \mathcal{U})$ or $(-\mathcal{U}, 0)$. In a similar way as depicted by the red lines for the inter-arrival times between zero-crossings (see response to your SPECIFIC COMMENT on l.1), the lengths of the inter-arrival times between excursions are shown by blue lines in the bottom-plot. In this case, the inter-arrival times are considered only for the positive threshold $\mathcal{U}$. As observed, the periods of CWS are not equivalent to the inter-arrrival times between excursions. A period of CWS might enclose several excursions, as well as several periods of CWS might be embedded inside an interval between two consecutive excursions.

Refer to the modifications to the manuscript mentioned in our response to your SPECIFIC COMMENT on l.1.

We have included the reference to [Rice, 1944] and [Kristensen et al., 1991] in the Introduction of the manuscript.

l.132 (also eq.2, l.107-109): which averaging interval is used for the σ_u here? Is it for each 10-minute period, or over the entire 5-day dataset?

We now make it clear in the text, L.129:

In Eq.(2) and through this document, we refer to $\bar{u}$ and σ_u as the values calculated over 10-minute periods unless a distinction is clearly stated

l.133: do you mean that taking A=0.3 means here that $I_u \leq 0.02$ due to the mean wind speed value (presumably ≈15 m/s)? This is not clear. (Or why not pick A based on Iu?)

Since now we are analyzing a longer data set from the FINO data with variable values of $\bar{u}$ and σ_u, this sentence is not valid anymore. Therefore it has been removed from the manuscript.

l.134: The values of ε are not provided in Table 2.

This sentence has been removed from the manuscript. As the value of ε is now calculated for each individual 10-min period (based on σ_u), there is not such a single value of ε at each height H.

l.161: There is not a simple 'clear power-law decay' for all values of A; in Fig.5 one sees a curved line which becomes straighter for rarer longer T_c.

The apparent curvature in the original log-log-plot of the PDFs decreased with the larger data set. More accurate power law fits are obtained (see Figs. 3 and 4 in the manuscript).

l.162: the finding 2< α <3 also means that the PDF can't integrate to 1 (its normalization constant is undefined), consistent with the fact that the lines are curved particularly at more common (shorter) T_c. The distribution is more like a stretched exponential or some other extreme value PDF. You cite Clauset/Shalizi/Newmann2009, but are still fitting a straight line on log-log (which they advised against) despite evidence that the power-law has a limited range of application for T_c.

Thank you for this critical comment. We follow the recipe for analyzing power-law distributed data provided in [Clauset et al., 2009], including estimating a lower bound on power-law behavior.

We now make it clear in the text, L.165:

The corresponding exponents α are calculated following the procedure proposed by [Clauset et al., 2009] and described in Appendix D.

We would also like to thank you for mentioning 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.

Fig.5: the horizontal axis has 1/3 empty space, and should be reduced; one can also then see more clearly where the curves become flat or not.

Thank you for noticing. We modified Fig. 5 (Now Fig.4) in the revised version of the manuscript.

Fig.9: there is no scale on the p(T_c) axis, spanning (apparently) 8 orders of magnitude; please include scaling factors and reduce empty space (extra 3-4 orders of magnitude on vertical axis and 50% horizontally).

Thank you for noticing. We added a scale to the axis in Fig. 9 and reduced the empty space.

Fig.9b caption: mention dotted red horizontal line here also.

Thank you for the recommendation. The line is now mentioned in the caption.

l.49: the mean and variance constraints demand that $\alpha < 2$ and $\alpha < 3$ respectively, but these are weaker constraints than that on the PDF itself ($\alpha < 1$); thus I recommend removing this phrase.

Thank you, we removed this phrase.

l.245: "very long" needs to be quantified, especially because you have used only a few days of data.

Thank you for the comment. The values of the longest periods of CWS are provided in Table 2 and Table 3 in the manuscript. Additionally, the comparison shown in Fig. 7 in the manuscript allows the relation of the lengths of the periods T_c to the large eddy turnover time (T_{int}) of the flow.

In the conclusion, L.269,

It is shown that the probability distributions $p(T_c)$ for offshore data exhibit a power law decay $p(T_c) \propto T_c^{-\alpha}$ for very long events (i.e. hundreds of seconds).

and L.276,

We found examples of T_c significantly larger than 100s, which correspond to spatially extended structures over sizes larger than 1km (...)

refer to the actual lengths of the periods.

l.246-7: you state "offshore conditions maintain a more unperturbed ABL", but compared to what? What (normalized) metric are you invoking to state this?

We mean compared to onshore conditions. see L.132:

We expect offshore wind to provide a better representation of undisturbed, or less disturbed conditions within the ABL compared to onshore data. Therefore, the possible effects of onshore orographic conditions on the CWS structures are diminished.

L.272 has been modified to accordingly:

Given that offshore conditions maintain a more unperturbed ABL compared to onshore, we demonstrated (...)

l.255: "proved the turbulent nature of the wind speed" does not make sense as a statement alone, and without saying how. What does this mean, is this statement necessary?

By proving the decay E(f)$\propto$ f$^{-5/3}$ in Sec. 3.4 we confirm the turbulent nature of $u(t)$ during the periods T_c.

L.280 has been modified:

Based on the spectral properties, we proved the turbulent nature of the wind speed $u(t)$ during the periods T_c.

l.261-2: the spectral gap is an effect, it does not cause effects; maybe state "phenomena related to the spectral gap".

Thank you for the correction. It has been included in the text. L.286

(...) or whether they are indeed consequences of larger-scale interactions of the atmospheric boundary layer, like phenomena related to the spectral gap [Larsén et al., 2016].

l.268-270: how do weak-turbulence periods cause "critical loads"? I suggest removing this phrase, unless you can explain and justify. Similar for "resonance". The justification on l.281 and later is ok (though it is a weaker effect than anti-correlated coherent turbulence across the rotor).

You are right. There is no justification for this rigorous statement. We have removed this sentence from the manuscript.

l.298, eq.(A1): there needs to be some minimum x and/or alpha<1, otherwise C is undefined, i.e., the integral of p(x) from 0 to infinity does not converge. You state simply "alpha>1" later in Appendix B, but this constraint should be mentioned here. In App.B you do assume an x_{min}, without explanation.

You are right. A more complete definition of the variables in Eq. (A1) has been now introduced.

L.329 to L.332 have been modified:

... for $x \geq x_{min}$ with the characteristic exponent α and a constant $C = e^c$. The minimum value x_{min} holds for the lowest limit of the power-law. The exponent α >1, otherwise $\int_0^\infty x^k p(x)$ does not converge.

l.319: $\leq$ should be $\geq$ here; i.e., the mean and variance constraints demand that alpha<2 and alpha< 3 respectively, but these are weaker constraints than that on the PDF itself (alpha<1).Given the latter, I would suggest removing the statement about mean and variance, unless you wish to move it to App.B add conditions on it with the use of x_{min}.

Thank you for the recommendation. In fact it made more sense to move the whole paragraph about the statistical moments to Appendix C (Appendix B in the previous version of the manuscript). That of course includes the sentences about the mean and the variance of x.

l.322-3 is the sentence about seismic events relevant here?

Not really, the sentence has been removed. Thank you for the recommendation.

l.370: should there be a comma between 0.9 and 1 for α_L?

Thank you for noticing. It has been corrected.

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

References

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