Authors' response to Anonymous Referee #2:
We, the authors, are very thankful for the detailed and constructive comments and greatly appreciate the willingness to review our manuscript. Please find our responses below. The original comments are shown in **bold** and the respective answers below. Excerpts of the manuscript are shown in *italic writing*, whereas additions are written in blue and deleted parts in ~~red~~. Thank you very much.
Specific comments:

1. **You should not have footnotes in Abstract. Abstract should be a stand-alone section without references to the rest of the paper.**
   This will be corrected by placing the description of intermittency in section 1.

2. **P1, L11. "The dynamic wind interacts: : :" What is a dynamic wind? This might imply that there is a static wind, which I never heard of. Wind is movement of air, thus it is dynamic by definition. Why not saying "Wind interacts: : :"**
   What was meant is that the wind speed is not static. We want to stress here that the wind, which interacts with the turbine, contains fluctuations/turbulence. We changed the text accordingly:

   The ~~dynamic~~ turbulent wind interacts with the system dynamics, resulting in the output parameters of a wind energy converter system such as power, mechanical loads or other quantities of interest.

3. **Not sure what is your rule to italicize words. I have nothing against italicizing the important words and terms, but in your manuscript you are using it for that purpose, as well as for the names of some instruments, modules, etc. I suggest you use it only to highlight important words.**
   This will be corrected in the updated manuscript and initialization will be limited to important words and phrases.

4. **Citations in the text should be from oldest to the latest. For example, P1, L1 has citations that are in a random order; similarly citations at the end of P1 are also randomly listed. Please correct that throughout the text.**
   This will be corrected in the updated manuscript.

5. **P1, L20. When discuss the non-Gaussian characteristics of wind, you should mention some of the atmospheric phenomena that create those winds; like downbursts, for example, which are quite frequent in Europe and elsewhere. Gust fronts are other phenomena associated with non-Gaussian winds. There are several papers by Giovanni Solari and his group on that subject. For instance, De Gaetano et al. (2014) demonstrated the non-Gaussianity statistics of some non-synoptic winds (see Figures 2, 3 and 4 in their paper). Papers like this would strengthen your study, as they show that there are some atmospheric phenomena that generate non-Gaussian wind statistics. De Gaetano P, Repetto MP, Repetto T, Solari G. 2014. Separation and classification of extreme wind events from anemometric records. Journal of Wind Engineering and Industrial Aerodynamics 126: 132–143. DOI: 10.1016/j.jweia.2014.01.006.**

   We thankfully notice the mentioned paper and like to include it in the introduction. At the same time, a clearer separation between the analyses of velocity *values* and velocity *increments* seems necessary in the manuscript. Therefore, the introduction was updated and we hope to clearly separate the velocity values and the corresponding statistics from increments, which is the focus of this paper. Increments characterize changes of the wind speed in a given time horizon, which is for example important for loads and the control system acting on actual wind values. Please find the updated version of the introduction at the end of this reply.

6. **Symbols in your equations are not the same as symbols in the text. Your u'(t) in the text does not look like u'(t) in equations. It is not italicized in the text. Please be consistent and correct these. (I gave an example of u'(t), but this holds for all of your symbols).**
   There are indeed discrepancies, which will be corrected in the updated manuscript.

7. **What is the reason behind using the wind speed interval between 7 m/s and 8 m/s and not some other or perhaps wider interval?**

   We chose the interval $7\,\mathrm{m\,s^{-1}} \leq \langle \mathrm{u(t)} \rangle_{\mathrm{10min}} \leq 8\,\mathrm{m\,s^{-1}}$ because typically a wind turbine is in a very stable operation in partial load conditions during those wind speeds. We wanted to exclude wind speeds close to cut-in as well as rated power. The interval gave us more than 22×10^6 data point considering 1 year of offshore data, which is more than enough. Regarding our analysis of increment PDFs, wider intervals gave very comparable results as shown in Figure 1 of this reply. Further, it has been shown in [1], Fig.5 that such a constraint will filter out intermittency effects caused by instationary conditions on large scales and thus enables to study more properly small scale turbulence effects. Therefore, we would like to stick to the original [7,8]m/s interval as the mean value and turbulence intensity match our TurbSim simulations. This aspect is further discussed in the following remark 8).

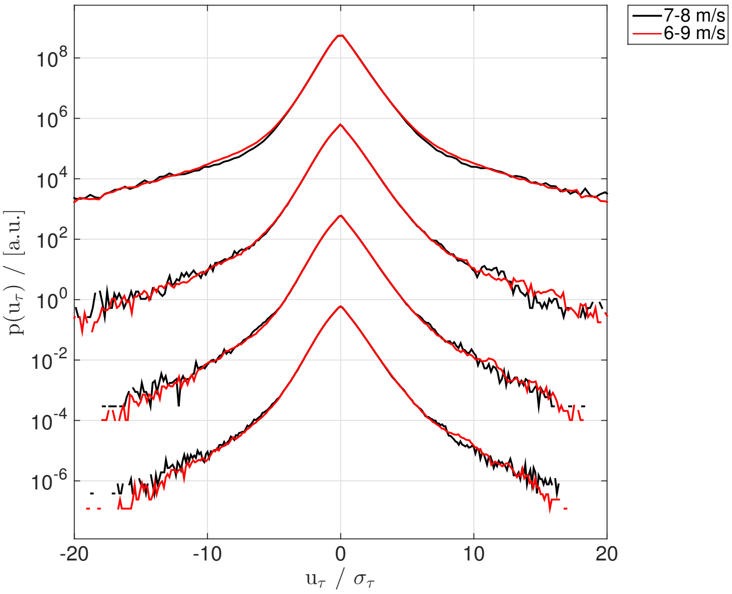

Figure 1: $p(u_\tau)$ for FINO1 data based on different 10min-mean intervals.

To clarify this, we added to the manuscript (p.4, lines 1 ff.):

10 Hz *data of one year were considered and ten minute records of* $7\,\mathrm{m\,s^{-1}} \leq \langle \mathrm{u(t)} \rangle_{\mathrm{10min}} \leq 8\,\mathrm{m\,s^{-1}}$ *were selected. The approximately 3700 records were then combined and used in this analysis, in order to ensure close-to stationary conditions. It has been shown by Morales et al. [1] that such a constraint will filter out intermittency effects caused by instationary conditions on large scales and thus enables to study more properly small scale turbulence effects. It should be noted that only the mean value of one ten minute record is within* $7.5 \pm 0.5\,\mathrm{m\,s^{-1}}$*. During* *this time span, samples outside of this interval are included. Tab. 1 shows...*

8. **You jumped right away to advanced statistical techniques, i.e. structure functions without showing some basic statistics. Please plot wind speed histogram of field measurements and fit it with Gaussian distribution. Synoptic winds show high degree of Gaussianity (please see the reference I provided above and some of the papers cited in that reference). Therefore, it is strange that your filed data are highly non-Gaussian. Thus, I would like to see a histogram and PDF of field measurements. It will also demonstrate that, while wind speed distribution is (maybe) Gaussian, the wind speed increment does not have to be Gaussian. I believe that further contributes to your paper.**

   This is a well known feature of stationary turbulence, u' is close a Gauss, whereas increment statistics increasingly deviate from Gaussianity [2], see also Morales et al. [1] for offshore wind data. We added such a statement in the revised paper to make this point clearer to the reader, p.3, lines 13 ff [1]:

   Going one step further in the sense of two point quantities, we will consider velocity changes during a time lag τ and refer to them as velocity increments,

$$u_\tau = u(t+\tau) - u(t) \tag{1}$$

   throughout this paper. It is important to distinguish between a statistical description of the fluctuations and the increments. In stationary turbulence, $u'(t)$ is close to a Gaussian distribution, whereas increment statistics increasingly deviate from Gauss [2], which is also shown by [1] for offshore data. The n^{th} order moments...

   It is shown in the mentioned paper that the intermittency in one-point statistics is caused by the non-stationarity of $\langle u\rangle_T$ and σ_T. Mathematically, this can be shown as done below

$$p(u) = \int p(u|\langle u\rangle_T) \cdot p(\langle u\rangle_T)\ \mathrm{d}\langle u\rangle_T. \tag{2}$$

   While $p(u|\langle u\rangle_T)$ might be Gaussian, the term $p(\langle u\rangle_T)$ reveals the large

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[1] The citation style in the revised manuscript will be consistent, e.g. (Frisch 1995)

scale instationarities and causes the non-Gaussian distribution of $p(u)$. We believe that the introduction of the manuscript should clearly state the difference in analyzing the wind speed (fluctuations) and the increments. Therefore, we changed the introduction to clarify, please find the revised version at the end of this reply. It should be clear now that only velocity increments are analyzed in our paper.
In Section 2 we focused on methods used in our analyses along with relations we found necessary to follow those approaches. As mentioned in the beginning of Sec.2, we purposely did not give a complete overview of methods to describe wind speed time series. Morales et al. [1] give a detailed description of statistical methods that are used to characterize offshore data exemplary. Therefore, we limit the description in Sec. 2 to the aspect used in our analyses (increment distributions) with referring the reader to Morales et al. for further details. In addition to the new introduction, we clarified this aspect in Sec. 2 as follows p. 3, lines 1 ff.:

In this section, we give a brief overview of the methods used in the industry standard and beyond, along with their mathematical background, without claims of completeness. Further, the methods of data analysis used in this study are introduced. We refer to Morales et al. for a more detailed elaboration. A general first step...

9. **Table 1 cuts a sentence in half. Please organize the text so that you don't have these discontinuities. It decreases the readability of your manuscript.**
We will correct this issue before uploading the new manuscript, however, I think a final placement of figures and tables is still to be done due to the two-column layout of the journal publications.

10. **P2, L78. If I am correct, you are using only the interval [7, 8] m/s. That being said, what extreme events are you referring to when you say extreme events are not reflected correctly using standard model.**
We are using the interval $7\,\mathrm{m\,s^{-1}} \leq \langle \mathrm{u(t)} \rangle_{\mathrm{10min}} \leq 8\,\mathrm{m\,s^{-1}}$, so the mean wind speed of a 10-minute block is in the interval [7,8]m/s. As shown in Figure 1 of the manuscript, we are analyzing time scales of $\tau \leq 60$s, which are relevant for the turbine dynamics. So by extreme events we are referring to extreme velocity increments of multiple standard deviations σ_τ on small time scales below one minute *within* a 10 minute block of $7\,\mathrm{m\,s^{-1}} \leq \langle \mathrm{u(t)} \rangle_{\mathrm{10min}} \leq 8\,\mathrm{m\,s^{-1}}$. We changed the manuscript accordingly, p.4, ll 7,8:

As shown in Tab. 1 and Fig. 1, certain characteristics of a wind speed time series, extreme ~~events~~ velocity increments in particular, are not reflected correctly using standard methods. In this paper,...

11. **P6, L1. Why is this spatially averaged wind speed more appropriate to describe the wind speed conditions than a single point measurements? Please explain.**
    Please refer to our responses to the first referee's comments as this issue is addressed there.

12. **P6, L910. This sentence has too many semi-colons. Please reformulate this sentence in order to remove these unnecessary semi-colons.**
    We reformulated this sentence to:
    The vacuum-casted rotor blades are based on a SD7003 airfoil profile. Further details on the turbine design are described by [...]. For details about the blade design, see [...].

13. **P6, L27. Why did you decide to use only a single hot wire signal for the comparison in Section 4.2 and not the spatially averaged data that you used for flow characterization?**
    Please refer to our responses to the first referee's comments as this issue is addressed there.

14. **What are the uncertainties and errors in all your measurements (wind tunnel, filed measurements, thrust, etc.)? Uncertainties in measurements should be well documented.**

    The offshore data is publicly available and uncertainties are well documented. For the respective anemometer, which was used in our study, the uncertainty is $\approx 3\%$ [3]. We suggest to add this information along with the respective citation to the manuscript.
    For the experimental data, we estimate the statistical error of the increment PDFs by $err \approx 1/\sqrt{n}$, where n is the number of events in each bin of the respective increment. For better judgment of the statistical significants of extreme events, we mark every bin with an error $< 10\%$ ($n < 100$) with a red $\times$ as exemplary done for Fig. 11(b) of the manuscript below:

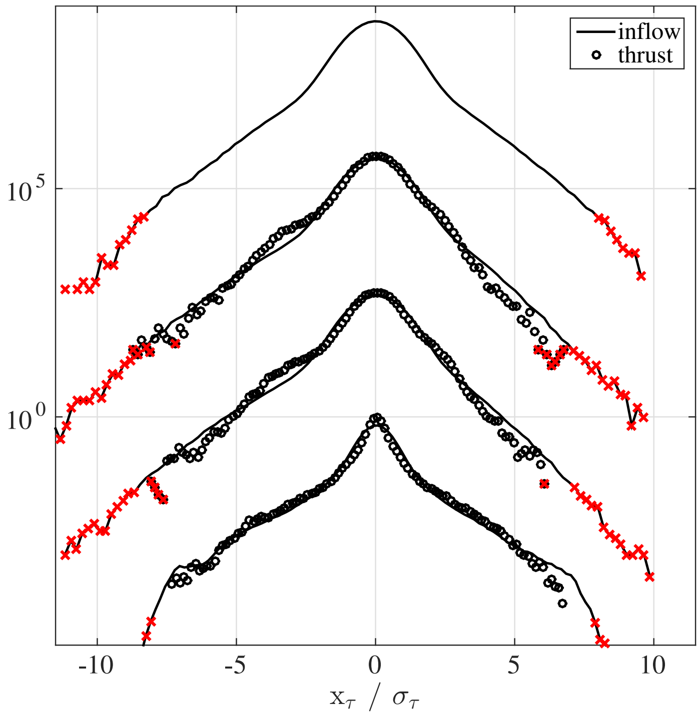

Figure 2: Increment PDF of inflow and thrust data. Data point with an estimated error exceeding 10 % are marked in red.

We suggest to describe this procedure and to mask values with a statistical error exceeding 10% for every increment-PDF shown in the updated manuscript,.

15. **In Figure 6, is the time series of wind speed synthetically created or is it from the wind tunnel measurements (or maybe field measurement)? Either way, that time series looks very artificial to me. Also, you said that your field measurements are in the interval [7, 8] m/s, but your wind speeds in Figure 6 are around 5 m/s. Is it due to the scaling or something else? Please explain.**

    The wind speed time series shown in Figure 6 is based on hot wire measurements upstream of the turbine during the intermittent inflow created by the active grid, which will be formulated more clearly in the updated version of the manuscript p.9, lines 3 ff:

    Fig. 6 shows examples of the time series of the four different signals, filtered and unfiltered. The graph in Fig. 6(a) shows the wind speed during the intermittent inflow upstream of the turbine. The other *graphs show the simultaneously recorded signals of the turbine.*

Due to the blockage of the turbine, the wind speed shown in this figure is smaller than 7m/s, which is the approximate wind speed at the rotor's position *without* the turbine being installed, please see section 4.1.

16. **P10, L6. What is the purpose to analyze scales that cannot be produced in your wind tunnel? That length scale cannot be replicated inside of your chamber.**
The largest *time* scale we analyze is $\tau = 2\,\mathrm{s}$. Applying Taylor's hypothesis gives a length scale of 14 m, which is larger than the test section. However, Taylor's hypothesis gives an idea of the length scale corresponding to a time scale τ. This does not mean that such a large structure is present in the test section at on point of time. Further, Knebel et al. [4] show experimentally that velocity time series with an integral length scale larger than the grid itself can be created in the wind tunnel with the active grid. We do think that it makes sense to analyze a time scale of $\tau = 2\,\mathrm{s}$. We reformulate the manuscript at p.10, lines. 6 ff:

    The largest scale considered is $\tau = 2\,\mathrm{s}$~~*, which corresponds to approximately 14* m *and is thus larger than the test section of the wind tunnel.*~~. *Thus, the turbine experiences a flow situation corresponding to a 14* m *structure in the wind field having an impact on the model turbine.*

    The interpretation of a 14-m structure being present at one time in the wind tunnel is misleading, although velocity changes in the range of seconds can be created. The reformulated section should clarify this.

17. **Your Table 2 is very confusing. What does the number 0.067 represent? That is, what is the column between "rotor diameter" and "order of blade length"?**
In the original Table 2, each column corresponds to one of the four time scales τ considered in the increment analysis. The number 0.067 represents the time scale of $\tau = 67\,\mathrm{ms}$. We suggest to update the table for better clarity, please find it below.

	scale 1	scale 2	scale 3	scale 4
time scale τ [s]	2	0.08	0.067	0.025
length/D [-]	≈ 24	1	≈ 0.8	0.3
physical object *	-	rotor diameter	-	order of blade length

Table 1: Overview of scales considered in relation to certain characteristic turbine lengths. The time scales τ were used the the analysis. To get an idea of the spatial dimension, Taylor's hypothesis is used to transfer from time to space with $\langle u \rangle \approx 7\,\mathrm{m\,s^{-1}}$. The obtained length scale is expressed as multiples of the rotor diameter for better comparison. The length is further related to physical objects of the turbine to get a sense of the dimensions.
*) The physical object relates the length scales based on Taylor's hypothesis to dimensions of the model wind turbine.

18. **P11, L3. ": : : analysis, two different, purposely created: : :" Please reformulate this sentence. Sounds strange.**
    We suggest to reformulate this sentence to:
    Throughout the following analysis, two different~~, purposely created~~ flow situations will be considered and used as inflow conditions for the model wind turbine.

19. **P17, L15. Vortex shedding, i.e. frequencies at which vortex shed is defined by the Strouhal number, which in turn depends on the Reynolds number. That being said, how is that shedding does not depend on fluctuations in inflow? Please elaborate. If needed, please take a look at Zdravkovich's books on flow around circular cylinders.**
    As mentioned, the shedding frequency is defined by the Strouhal number. The shedding also occurs during laminar inflow and does therefore not depend on the fluctuations in the inflow.

    The purpose of this example is to show that an object in the flow might experience dynamics/fluctuations that do not result from velocity fluctuations in the inflow. Such effects might occur in the experiments, however, we try to focus on the turbine dynamics that *do* result from the inflow turbulence. As this example might cause more confusion than adding completeness, we suggest to delete the specific example and reformulate as follows:

    Also, there might be aerodynamic effects that are of even higher frequency than the inflow fluctuations, and are therefore not captured due *to the filtering.* ~~*As a straightforward example, a laminar flow passing a cylinder results in a well-defined frequency due to von Kármán vortex shedding, cf.[...]. The shedding does result from the inflow, although not being related to the fluctuations. Thus, aerodynamic...*~~. *Such effects at the rotor are possibly excluded by the low frequency filtering. This study, however, focuses on dynamics caused by the inflow turbulence.*

20. **P17, L16. Based on the circular cylinder example, how did you conclude that some aerodynamic effects might be excluded due to low frequency filtering? You use a "Thus" at the beginning of that sentence and I do not see how that claim results from the previous discussion. Please explain.**
    As mentioned in the previous comment, we mention effects of higher frequency than the inflow fluctuations. This implies that those frequencies are larger than the cutoff frequency of the low pass filter, cf. Fig. 5 in the manuscript. However, as this example will be deleted as mentioned in the previous comment, we do not think that a more detailed description is needed in the manuscript.

21. **The last sentence in the Discussion section is confusing. To me, it sounds like you are saying that the focus of this study is to analyze what is presented in the study, which is redundant. Please reformulate or explain what information you want to convey in that sentence.**
    The last paragraph of the discussion states that we do not claim full scalability due to the mentioned reasons. We agree that the last sentence does not really fit in here as mentioning the main findings should be done in the conclusion. We delete the last sentence of the discussion.

22. **I believe you should emphasize more on the importance of your study in the Discussion section. Try to relate your findings, at least qualitatively, with the real atmospheric conditions. Also, what would be the application of your study? When can we expect non-Gaussian velocity increments and when are they Gaussian in real atmosphere? Moreover, are they ever Gaussian? All these questions could be addressed in Introduction and/or Discussion. Providing answers to those and similar questions would greatly improve the readability and contributions of your paper.**

In this study we focus on time scales $\tau \leq 60\,\mathrm{s}$ regarding atmospheric data. We show in Fig. 1 that those increment PDF are far from Gaussian as also shown in the cited works. Throughout this paper, we concentrate on the discrepancy between the intermittency of the data and the Gaussian assumption by the industry standards. The application is to show whether this discrepancy is relevant for wind turbines. This is stated in the conclusion. However, we agree that his should be stated more clearly. We will add to the introduction p.2, line 19.:

It is not clear to what extent non-Gaussian flow conditions transfer to turbine data. At the same time, this is a very important aspect in the design process of wind turbines and in the wind field models used. Wrong assumptions of the conversion from turbulence characteristics to wind turbine data might lead to faulty dimensioning and problems in the integration of wind energy in the power grid.

23. **P18, L1. "Our results show: : :" Please reformulate this sentence. Not clear what you want to say.**
    What was meant is that the intermittency in the inflow is not filtered by the turbine so that the turbine data is intermittent in a similar way. We reformulate the sentence as follows:
    Our results ~~show no~~ do not show any filtering of the intermittent features of wind speed fluctuations found in real wind fields by the turbine. Consequently one should be aware that wind characteristics, which are not reflected in standard wind field descriptions, e.g. the IEC 61400-1, have a significant impact on wind turbines.

24. **Lastly, I advise the authors to find a native English speaker to proofread the manuscript.**
    The updated manuscript will be carefully proofread.

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[1] Morales, A., Wächter, M., and Peinke, J., "Characterization of wind turbulence by higher-order statistics," Wind Energy, Vol. 15, No. 3, 2012, pp. 391–406.

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[3] Westerhellweg, A., Neumann, T., and Riedel, V., "Fino1 mast correction," Dewi magazin, Vol. 40, 2012, pp. 3.

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On the impact of non-Gaussian wind statistics on wind turbines - an experimental approach

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Abstract. The effect of intermittent[1] and Gaussian inflow conditions on wind energy converters is studied experimentally. Two different flow situations were created in a wind tunnel using an active grid. Both flows exhibit nearly equal mean velocity values and turbulence intensities, but strongly differ in their two point statistics, namely their distribution of velocity increments on a variety of time scales, one being Gaussian distributed, the other one being strongly intermittent. A horizontal axis model wind turbine is exposed to both flows, isolating the effect of the differences not captured by mean values and turbulence intensities on the turbine. Thrust, torque and power data were recorded and analyzed, showing that the model turbine does not smooth out intermittency. Intermittent inflow is converted to similarly intermittent turbine data on all scales considered, reaching down to sub-rotor scales in space, indicating that it is not correct to assume a smoothing of wind speed fluctuations below the size of the rotor.

1 Introduction

Wind energy converters (WECs) work in a turbulent environment and are therefore turbulence driven systems. The ~~dynamic~~ turbulent wind interacts with the *system dynamics*, resulting in the output parameters of a wind energy converter system such as power, mechanical loads or other quantities of interest.

Generally, the characteristics of the output dynamics of a WEC need to be understood in detail for multiple reasons. Power fluctuations have been reported in numerous studies, causing challenges in grid stability (e.g. Chen and Spooner, 2001; Carrasco et al., 2006; Sørensen et al., 2007). Drive train and gearbox failure rates remain high, adding to the cost of energy since gearboxes are among the most expensive parts of WECs. These types of failures are likely to be linked to torque fluctuations (e.g. Musial et al., 2007; Feng et al., 2013). Next, turbulent wind affects extreme and fatigue loads, which is clearly related to the lifetime of WECs (Burton et al., 2001).

Wind dynamics in the atmospheric boundary layer have been investigated extensively. Here, one has to differentiate between analyses concerning the statistics of the wind speed values and velocity increments. The wind velocities might become anomalously distributed due to large scale meteorological events like downbursts or thunderstorms (e.g. De Gaetano et al., 2014).

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[1] ~~It should be noted that, throughout this paper, intermittency refers to a non-Gaussian, heavy-tailed distribution of increments as defined in Sec. ??.~~

Velocity increments, on the other hand, characterize statistically the temporal aspect of fluctuations, whose non-Gaussian statistics is well-known from small scale turbulence (e.g. Frisch, 1995). Active systems, like wind turbines as discussed here, adapt to actual wind situations, thus we focus in this contribution on wind speed changes within seconds, i.e. by the corresponding increments. Numerous studies report on non-Gaussian characteristics of wind speed ~~fluctuations~~ increments, see (e.g. Boettcher et al., 2003; Liu et al., 2010; Morales et al., 2012; Wächter et al., 2012). Further, findings of non-Gaussian wind statistics have been implemented in simulations by a variety of methods, see (e.g. Nielsen et al., 2007; Mücke et al., 2011; Gong and Chen, 2014).

In the field of wind energy research, it is still unclear to what extent wind dynamics transfer to the parameters of a WEC such as loads, power etc. Most likely, this depends on the relevant time scales, which change with the system dynamics. Therewith, the conversion from wind to power, loads etc. vary with the turbine type. Consequently, it is of importance what scales in time and space are relevant to quantify the impact of turbulent wind on WECs (van Kuik et al., 2016) and scale dependent analyses become necessary.

Mücke et al. (2011) found that intermittent inflow conditions do not affect rain flow distributions of the torque significantly. However, similarly intermittent torque ~~fluctuations~~ increments based on a numeric wind turbine model used in FAST in combination with AeroDyn (Moriarty and Hansen, 2005) were found. Gong and Chen (2014) investigated the short and long term extreme response distributions of a wind turbine during Gaussian and non-Gaussian inflow conditions using the aeroelastic tool FAST (Jonkman and Buhl Jr, 2005). The extreme turbine responses to non-Gaussian inflow were considerably larger than the ones to Gaussian wind. However, Berg et al. (2016) recently reported a vanishing effect of non-Gaussian turbulence on extreme and fatigue loads based on large-eddy simulation (LES) generated wind fields in combination with aeroelastic load simulations using HAWC2 (Larsen and Hansen, 2007). It was concluded that non-Gaussianity in sub-rotor size eddies are filtered by the rotor. In contrast, Milan et al. (2013) showed that, based on field data, multi-MW WECs convert intermittent wind speeds to turbulent like, intermittent power with fluctuations down to the scales of seconds. Even on the scale of an entire wind farm, intermittent power output was reported. To summarize, different simulations and data from real turbines deliver an inconclusive answer on our posed question on the conversion from turbulent inflow to wind turbine data. It is not clear to what extent non-Gaussian flow conditions transfer to turbine data.

With the present work we contribute wind tunnel experiments to the ongoing discussion on the conversion process of non-Gaussian wind statistics to wind turbine data such as power, thrust and torque. A model wind turbine and an active grid for flow manipulation were used in order to examine to what extent Gaussian distributed and highly intermittent wind speeds affect the model turbine dynamics differently.

This paper is organized as follows: Sec. 2 gives an overview of commonly used methods to characterize wind speed time series, parts of which are applied to offshore measurement data and simulated wind speed time series. Mathematical tools used throughout this paper are introduced here. Next, Sec. 3 describes the experimental methods used, including the setup, the definition of examined quantities and their processing. Sec. 4 shows the results of the experiments, which are discussed in Sec. 5. Finally, Sec. 6 gives the conclusion of the findings.

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