Authors' response to Anonymous Referee #1:

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** with the respective answers below. Excerpts of the manuscript are shown in *italic writing*, whereas additions are written in blue and deleted parts in ~~red~~.
Please note that the format of citations in manuscript excerpts might be changed.
Thank you very much for your efforts,

Jannik Schottler on behalf of all authors

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1)
Main comment is on the impact to loads. In the introduction, and later in the paper, references to past literature documenting that their is a connection between velocity increments and loads, but the nature of the connection is not elaborated on. Could some of the findings of those papers be summarized for context? For example, are the impacts more important for fatigue loads or extreme loads? In the companion paper, figure 11 shows a reduction in TKE during wake steering. If one is considering wake steering, to what extent would a reduction in TKE counter-balance a change in increment velocity? Is there a method to weigh these two changes? Is there a connection to loads on specific components (blades, drivetrain) or failure modes? Details in this regard would help to contextualize the findings.

Thank you very much for this constructive comment. We want to answer the different aspects separately, for better clarity. Afterwards, we give some more details for completeness of the discussion.

In the introduction, and later in the paper, references to past literature documenting that their is a connection between velocity increments and loads, but the nature of the connection is not elaborated on. Could some of the findings of those papers be summarized for context?

To what extent intermittent characteristics of atmospheric turbulence transfer to turbine data such as torque, moments, power, etc has been investigated experimentally and numerically. Details are subject of discussion within the research community, however, relevant studies are summarized here: Milan et al. [9] analyzed power data of full scale wind turbines and of a whole wind farm, finding heavy-tailed power increments on time scales of the order seconds, suggesting intermittency is transfered from wind to power. In a wind tunnel experiment using an active grid and a model wind turbine [1], we showed that non-Gaussianity of velocity increments was transfered to power, torque and thrust data of the model turbine on the lab scale (that is the same model wind turbine as denoted *ForWind* turbine in the manuscript).
In a numeric study, Mücke et al. [10] found that intermittent flow conditions result in similarly intermittent torque increments using FAST [11] in combination with Aero-

Dyn [12]. In the manuscript, we suggest to summarize this in the introduction:

> p.2, ll.25 ff:
>
> *[...]. To what extent statistical characteristics of velocity increments are transfered to wind turbines is of current interest throughout the research community [14]. ~~We~~ Schottler et al. [1] found a transfer of intermittency from wind to torque, thrust and power data in a wind tunnel experiment using a model wind turbine. Similarly, Mücke et al. [10] found a transfer of intermittency to torque data using a generic turbine model. Milan et al. [9] reported intermittent power data in a full-scale wind farm. We thus believed that distributions of velocity increments in wakes are of importance for potential downstream turbines as ~~extreme events~~ non-Gaussian characteristics are likely to be transfered to wind turbines in terms of fluctuating loads and power output. ~~Studies show this for a generic turbine model [10] , in a wind tunnel experiment [1] and by analyzing field data of a full-scale wind farm [9] . Those findings make an investigation of~~ Consequently, investigations of velocity increments in wakes become extremely relevant for active wake control concepts as well as for wind farm layout approaches. A further elaboration on the connection of non-Gaussian velocity increments and loads as well of power fluctuations is given in Section 4. This work is organized as follows. [...]*

For example, are the impacts more important for fatigue loads or extreme loads?

Despite the above findings (intermittency is transfered to turbine data), the question remains to what extent intermittent, non-Gaussion force statistics influence common ways to calculate fatigue and extreme loads. Berg et al. [15] reported a vanishing effect of non-Gaussion turbulence on extreme and fatigue loads based on an LES wind field in combination with HAWC2 [16]. However, in numeric studies the challenge is to generate synthetic wind field featuring correct statistics of both, velocity increments and velocity values. At ForWind, we use the Continuous Time Random Walk (CTRW) model, which is know e.g. from electron transport and molecular movement, in combination with LES to generate synthetic wind fields. An early version of this approach was used in [10], showing insignificant effects. Recent improvements allow for a more realistic generation of synthetic wind fields in the sense of one- and two-point statistics. Those wind fields were used by Schwarz et al. [17] in combination with a Blade Element Momentum approach and the NREL 5MW reference turbine in order to quantify the effects of non-Gaussian velocity increments on fatigue load calculations. Figure 1 shows the equivalent fatigue loads based on a rainflow counting. Results should be seen as preliminary and are taken from [17].

Clearly, the inflow conditions featuring intermittent velocity increments result in increased fatigue loads relative to the reference case featuring Gaussian statistics.

Summarizing, we believe that the non-Gaussian character of atmospheric velocity increments, on time scales affecting the rotor, do impact loads of wind turbines. However, it is important to notice that it is today not clear and a current research question, how intermittency affects common ways of load calculations (rainflow counting for example). This possibly strongly depends on details such as time scales etc. Proper numeric and experimental tools for investigations are being developed and so-

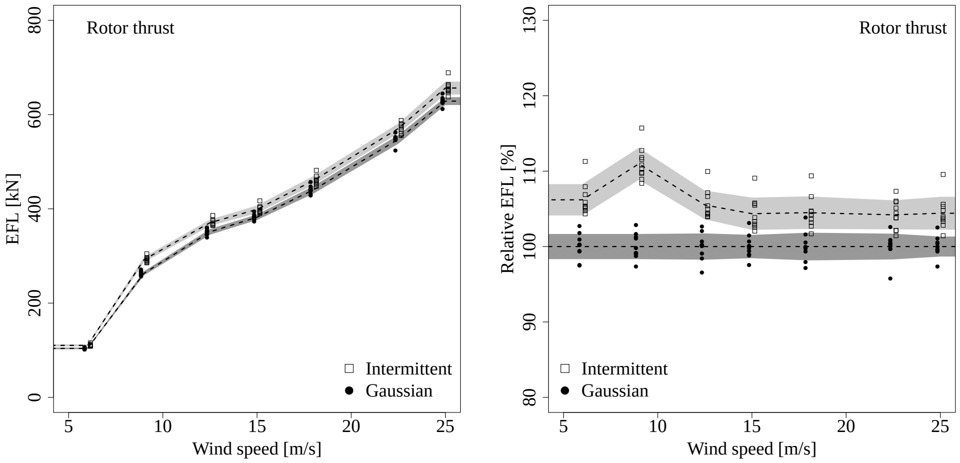


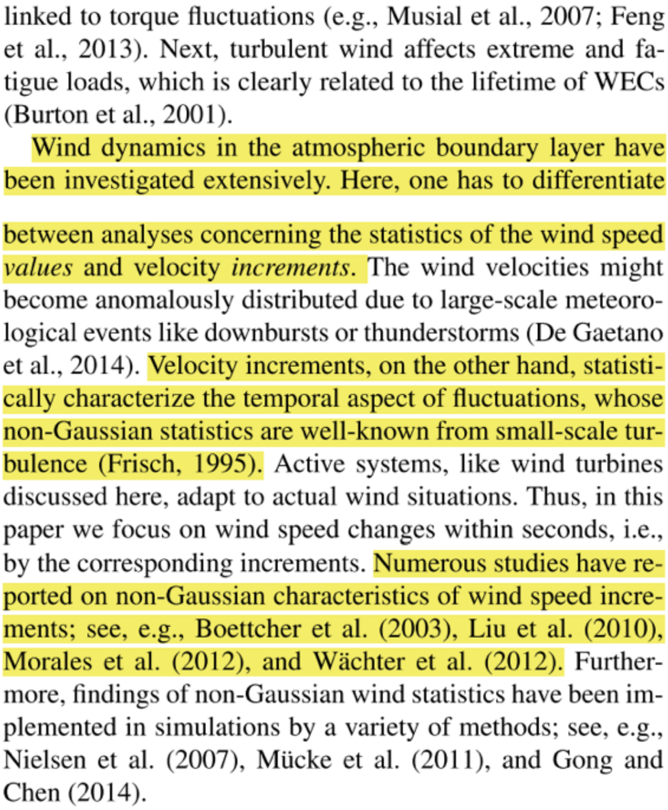
Figure 1. Effective fatigue loads, absolute (left) and relative (right) of the NREL 5MW reference turbine exposed to Gaussion and non-Gaussian wind fields generated with the CTRW model. Taken from [17].

phisticated studies are limited. Therefore, a complete and conclusive answer is not within the scope of this manuscript. Nevertheless, we do agree that this should be stated more clearly in the manuscript and that it should be elaborated in more detail. We suggest to update the discussion section as follows:

> p.15, ll. 5 ff:
>
> *This becomes important when assessing the applicability of active wake steering approaches, as a gain in power has to be balanced with a potential load increase, affecting maintenance costs and the lifetime of turbines overall.*
> *It should be noted that it is to date not clear to what extent high TKE levels and intermittent force data are affecting common ways of fatigue and extreme load calculations. This important aspects needs to be addressed in future works. Possibly, it strongly dependents on details such as considered time scales. In our opinion, it is likely that non-Gaussian inflow is linked to drive train, gear box or pitch systems failures, especially because those inflow characteristics are not accounted for in standard models used in the design process. The velocity deficit [...]*

In the companion paper, figure 11 shows a reduction in TKE during wake steering. If one is considering wake steering, to what extent would a reduction in TKE counter-balance a change in increment velocity? Is there a method to weigh these two changes?
We believe that a quantification of the impact of the inflow's TKE on e.g. fatigue loads of a turbine is a challenging tasks. To our knowledge a direct method is yet to be found. The same holds for intermittency. Thus, there is not a method to weigh both flow situations in terms of loads quantitatively. However, we do agree that some speculation about these questions can improve the discussion section of the manuscript. Please refer to the above changes (p.15,ll 5 ff).

Further Details:
It is a well-known feature of the atmospheric boundary layer that velocity increments (time scale: order $\sim$ seconds) feature non-Gaussian characteristics. This has been summarized in [1], Figure 2 of this reply shows a screen shot. In the wind energy context, this is of particular interest because those characteristics are not implemented in standard wind field models such as the Kaimal model, which is suggested to be used in the design process by the norm IEC 61400-1. Figure 3 shows a screen shot taken from [1], showing distributions of velocity increments of two time series, one is based on offshore measurements in the north sea (FINO1 measurement platform), the other one is based on a synthetic wind field based on the Kaimal model [7], generated in TurbSim [8]. Both time series are equal regarding mean values and turbulence intensity, however, as the graph shows, the distributions of velocity increments are not grasped correctly by the Kaimal model, which features purely Gaussian statistics. So far, it is clear that atmospheric wind features non-Gaussian increment statistics on small scales.



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 (De Gaetano et al., 2014). Velocity increments, on the other hand, statistically characterize the temporal aspect of fluctuations, whose non-Gaussian statistics are well-known from small-scale turbulence (Frisch, 1995). Active systems, like wind turbines discussed here, adapt to actual wind situations. Thus, in this paper we focus on wind speed changes within seconds, i.e., by the corresponding increments. Numerous studies have reported on non-Gaussian characteristics of wind speed increments; see, e.g., Boettcher et al. (2003), Liu et al. (2010), Morales et al. (2012), and Wächter et al. (2012). Furthermore, 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), and Gong and Chen (2014).

Figure 2. Screen shot taken from [1]. The highlightes references are [2, 3, 4, 5, 6].

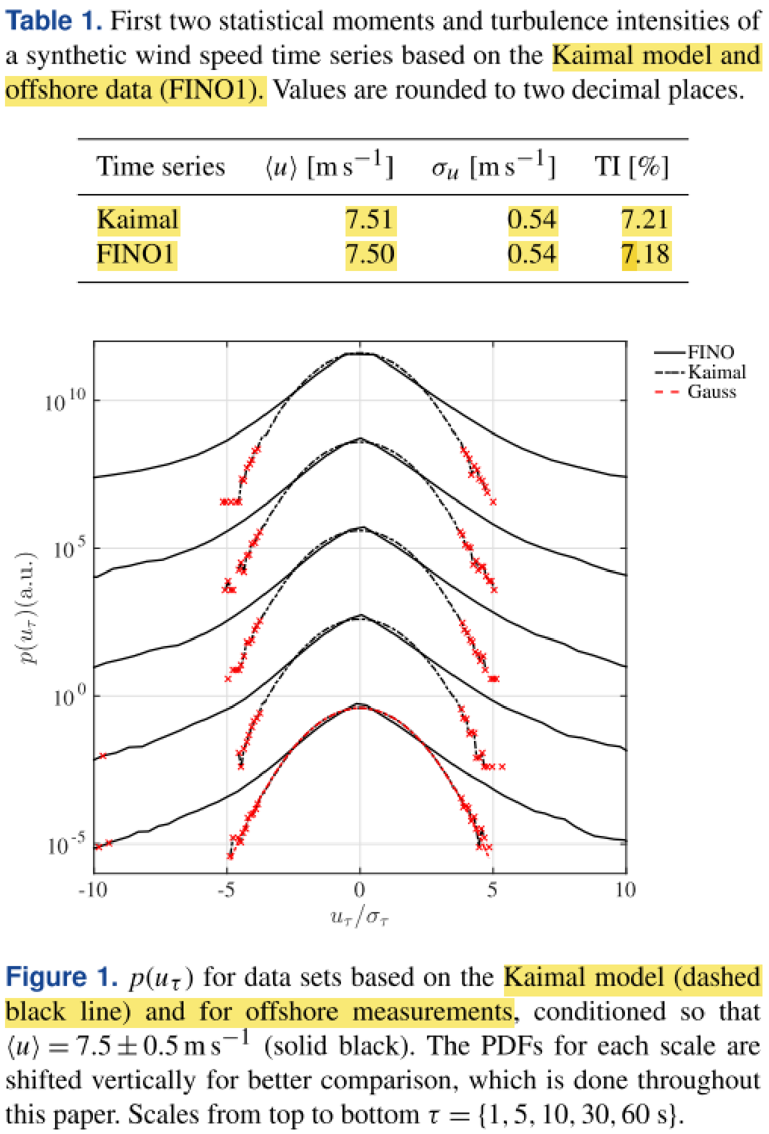


Table 1. First two statistical moments and turbulence intensities of a synthetic wind speed time series based on the Kaimal model and offshore data (FINO1). Values are rounded to two decimal places.

Time series	$\langle u \rangle$ [m s^{-1}]	σ_u [m s^{-1}]	TI [%]
Kaimal	7.51	0.54	7.21
FINO1	7.50	0.54	7.18

Figure 1. $p(u_\tau)$ for data sets based on the Kaimal model (dashed black line) and for offshore measurements, conditioned so that $\langle u \rangle = 7.5 \pm 0.5\,\mathrm{m\,s^{-1}}$ (solid black). The PDFs for each scale are shifted vertically for better comparison, which is done throughout this paper. Scales from top to bottom $\tau = \{1, 5, 10, 30, 60\ \mathrm{s}\}$.

Figure 3. Screenshot taken from [1]. FINO1 refers to offshore measurement data, Kaimal is a synthetic wind field based on the Kaimal model, generated by TurbSim.

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2)

Could the authors elaborate further on the connections to the companion paper. Would it make sense to bring the TKE analysis of the companion paper into this paper, and move the analysis of wake position to the companion paper? Feel free to reject this suggestion if I misunderstand the distinctions between the papers, My thinking is just that, for example, if only one of the papers dealt with estimating wake position, then this could make each of the papers more focused on specific effects. But, it would also be acceptable to further elaborate on the focus of the two papers, where they overlap and where they diverge.

Thank you very much for pointing this out and adding these constructive ideas to the discussion. Generally, the idea of dividing both manuscripts is the following: This paper here compares both turbines. Therefore, the turbine is the changing variable and we limited examined cases to one downstream distance ($6D$) and one inflow condition (uniform turbulence/grid). Comparing data of 2 turbines, 3 yaw angles, 2 distances and multiple inflow conditions would simply be too much for one manuscript. The means of comparison are the velocity deficit, the TKE and the intermittency parameter λ^2. The companion paper focuses on the impact of different inflow conditions. Therefore, the changing variable is the turbulence grid (no grid, uniform grid, shear grid) and therewith the inflow. The turbine was limited to one turbine only to keep the focus. Although both papers investigate the TKE in the wake, one main point in this manuscript is how findings are different/similar regarding both turbines, while the main point in the companion paper is how the findings change with different inflow conditions. Because of that, we would like to keep the distinctions as done in the discussion papers. However, we think it adds clarity to mention parts of this discussion in the introduction and suggest to reformulate more clearly:

p. 3, ll. 1 ff.

This work is part of a joint experimental campaign by the NTNU in Trondheim and ForWind in Oldenburg. ~~A~~ While this paper compares the wakes behind two different model wind turbines during one inflow condition, a second paper by [18] examines the influence of varying inflow conditions on the wake of one model wind turbine.

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3)

Finally, the difference in rotation direction between the turbine models is very interesting. The authors use this difference to explain the asymmetries in vertical transport and tilt, could it also explain differences in displacement for positive vs negative yaw observed in the companion paper? Does the size of observed vortices vary with whether the vortex shed by misalignment is rotating in the same direction as the wake?

Thank you very much for bringing up this interesting aspect. To address the first question, Figure 4 of this document shows the results of the wake center quantification as proposed in Section 2.2 of the manuscript. The figure is the basis of Table 2 of the

manuscript. As Table 2 of the manuscript and Figure 4 of this document show, the same deflection magnitude for either direction of yaw misalignment was found for the ForWind turbine. Differences occur behind the NTNU turbine only using the method described in Section 2.2 of the manuscript. Therefore, we cannot conclude with certainty that the direction of rotation is the reason for asymmetric deflections. If that hypothesis held, one would expect that the deflections behind the ForWind turbine would be asymmetric as well but the other way round, which it is not.
Consequently, one can only speculate about the reasons for the distinctions between the turbines in terms of asymmetric deflection regarding $\gamma = \pm 30°$. Intuitively, one would assume reasons are connected to the differences amongst the turbines, being:

- blockage
- geometry (tower, nacelle)
- rotor (airfoil, rotor tips,...)

In my opinion it is important that blockage/wind tunnel effect are more influential using the NTNU turbine, especially during yaw misalignment with a wake deflection. Wind tunnel effects might play a role regarding the distinctions between both turbines shown in Figure 4 of this document.

However, the data does not allow a certain reasoning, so its all a bit speculative.

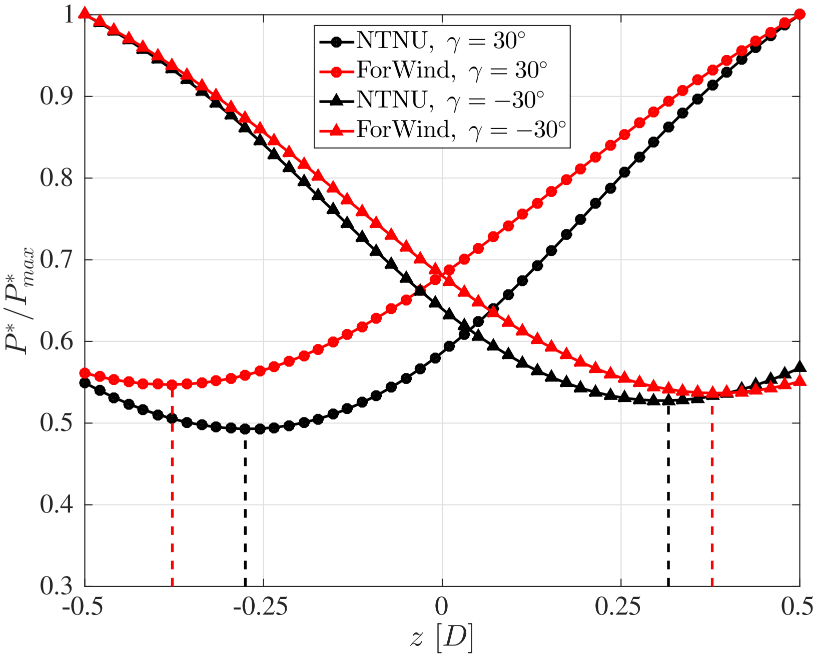

Figure 4. Potential power P^* as described in Section 2.2 of the manuscript for varying horizontal positions z. $x/D = 6$.

At the same, a "wake center" is somewhat a vague term. We use the method of a potential downstream turbine's power because we believe it is closest to the potential application of wake deflection studies. We only considered variations in z direction, which should be kept in mind.

Regarding the second question, I think this is a very interesting train of thought. Ideally, one would have to consider all three flow components for a proper interpretation of the evolving vortex pairs. However, only two components were recorded for the majority of this campaign. Those ($u(t)$ and $v(t)$) are shown in Figures 5 and 6 of this document for the ForWind turbine and the NTNU turbine, respectively. Showing both turbines (and thus both rotational directions), both yaw angles and both flow components, one can compare as much as the data allows. However, as the third flow component was not recorded, some speculation about the vortex pair is probably inevitable. Starting with the ForWind turbine (Fig. 5 of this document), we believe the plots show quite symmetric situations comparing positive and negative yaw misalignment. Confirming Table 2 of the manuscript, also the v component shows very symmetric contours, regarding position, shape and magnitude of the dipoles. One expects a strong horizontal velocity component at hub height towards positive z direction for $\gamma = -30°$ and in negative z direction for $\gamma = +30°$, resulting in two counter rotating vortex pairs (cf. Fig.6 of the companion paper). As the contours for $\gamma = -30°$ and $\gamma = +30°$ look very symmetric regarding $u(t)$ and $v(t)$, one cannot conclude that the shed vortices are much different regarding the direction of yaw misalignment.
Looking at Figure 6 of this document, contours behind the NTNU rotor are slightly asymmetric, which is expected based on Figure 4 of this document.
I believe, similarly as for the first question, one has to think about the differences listed above and some speculation is inevitable. To me, it is more likely that those asymmetries are caused by wind tunnel/blockage effects. Consequently, we do not believe that there is a clear connection between the size of the vortex pair and the direction of yawing / the direction of rotation.

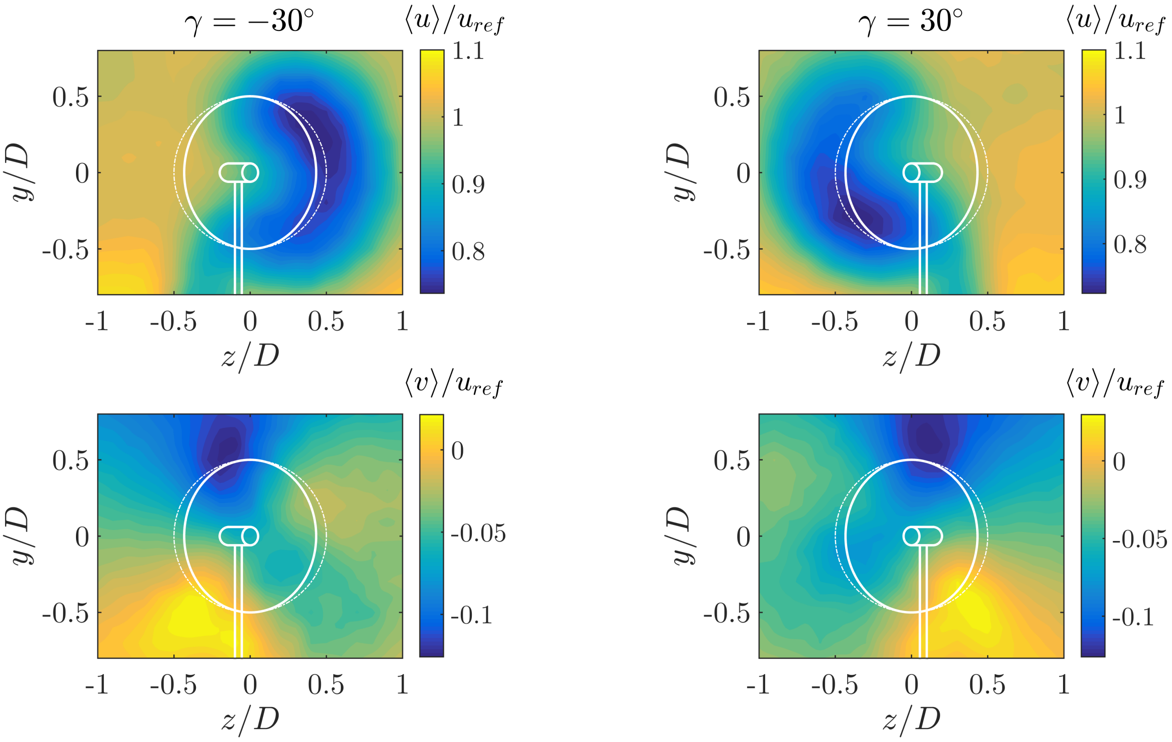

Figure 5. Wakes behind the ForWind turbine at $x/D = 6$. Left column: $\gamma = -30°$, right column: $\gamma = +30°$. Top row: $\langle u \rangle / u_{ref}$, bottom row: $\langle v \rangle / u_{ref}$.

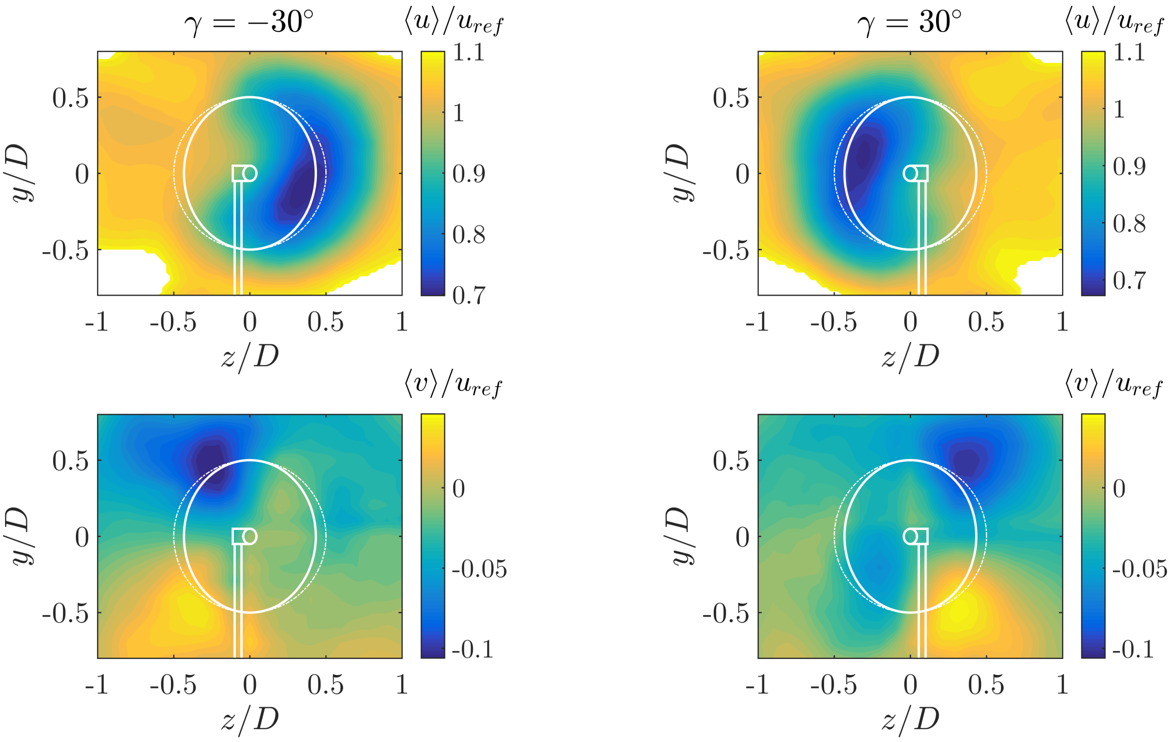

Figure 6. Wakes behind the NTNU turbine at $x/D = 6$. Left column: $\gamma = -30°$, right column: $\gamma = +30°$. Top row: $\langle u \rangle / u_{ref}$, bottom row: $\langle v \rangle / u_{ref}$.

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