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** 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)
Although the title clearly mentions the paper deals with a wind tunnel test, it would be good to exercise some caution in the text on the application of the results to the 'real world'.

Thank you very much for this valuable input to the discussion. We do agree that it is important discuss real life application of the findings and want to adapt the manuscript accordingly.
Generally the (scientific) interest in wind turbine wakes is closely related to the 'real world' as wake effects are known to cause an increase in the cost of energy. Therefore, a mitigation of wake effects would be economically beneficial for wind farm operators and turbine manufacturers. As described in the introduction, wake steering through intentional yaw misalignment is one concept potentially capable of mitigating wake effects in wind farms, however, prior to applying the concept, the effects have to be studied carefully in numeric simulations, experimentally and in field tests, all of which are currently done. Going towards the concrete finding of this study that are summarized in the conclusion, we think the formation of a curled wake during yaw misalignment is important when assessing the applicability of wake steering concept. Those flow conditions become inflow conditions for downstream turbines, therefore an inhomogeneous flow field is an important feature for resulting loads which need to be investigated when judging active wake steering methods. Similarly, the curled shape shows that line measurements at hub height are not sufficient when quantifying wake deflection magnitudes. This is stated in p.15, ll. 6-8 in the manuscript.

Next, a ring of super-Gaussian velocity increment surrounding the velocity deficit of a wake, thus having a significantly larger diameter than the rotor, is one main finding of this paper. The importance of those statistical characteristics are potential load increases. For a more detailed elaboration, please refer to comment/answer #1 of the Referee #1. In a 'real world' scenario, the applications are two folded:

- In wind farm layout optimization, the width of of a wake is a crucial parameter, especially for lateral turbine spacing. Our results suggest the width of a wake significantly increases when taking two-point quantities into account (here: λ^2). Exemplary, in a (laterally) densely spaced wind farm, a turbine might operate in free stream condition considering the velocity deficit, but might be affected by the ring of high λ^2 values shown in Fig. 7 of the manuscript. This difference becomes more clear looking at Fig. 10. Power *and* loads are being considered when optimizing a layout, loads are potentially strongly affected by the findings of the paper.

- As stated in the introduction, wake steering approaches through yaw misalignment are heavily discussed in the research community. The idea is to steer a wake away from a potential downstream turbine to mitigate power losses through wakes, thus gaining net power. Just as in layout optimizations, not only power but also loads have to be considered, which again might be affected by our findings: Looking at Fig. 13 for example at $z = -0.5, y = 0$ a potential in-line downstream turbine would experience more free stream velocity, thus a power increase. Taking two-point statistics into account however shows that the exact same location would experience flows featuring high λ^2 values. Please refer to comment #1 of referee #1 for a more detailed elaboration about the connection between loads and intermittency.

We suggest to formulate more clearly in the updated discussion section:

p.14, ll.8 ff:
Consequently, our findings should be considered in wind farm layout optimization approaches, where a wake's width ~~affects~~ is a crucial parameter for radial turbine spacing. As layouts are being optimized regarding power and loads, the latter might be significantly affected by taking into account intermittency and the resulting increased wake width. Possibly, the ring of non-Gaussian velocity increments [...].

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2)
The reported high thrust coefficients corresponds to rather high axial induction factors towards the turbulent wake state, in how far is this representative for real life turbines nowadays and how would this affect the observed wake shapes? Has there been any attempt to clarify the effect of operational conditions on observations (partial load. full load)

Thank you very much to pointing the attention to the high thrust for the ForWind turbine. We noticed a non-consistency here and want to correct it: Regarding Table 1 of the manuscript, the thrust coefficient of the NTNU turbine was calculated with subtracting the thrust caused by the tower. For the ForWind turbine, the value is based on the total turbine thrust, including the tower structure. This should be corrected in the manuscript and clearly stated. We apply the following correction of the ForWind thrust coefficient:

The tower structure of the ForWind turbine is simplified as a cylindrical structure of 4 cm diameter. At the inflow velocity of $\langle u(t) \rangle = 7.5 ms^{-1}$, the resulting Reynolds number is $Re_{tower} \approx 2.1 \times 10^4$. Based on Figure 1, the resulting drag coefficient of a circular cylinder and thus the tower is

$$c_{T,tower} \approx 1.2. \quad (1)$$

With the thrust on the tower being

$$F_{T,tower} = 2c_{T,tower}/u^2\,\rho\,A_{tower}, \quad (2)$$

we can now calculate the corrected thrust coefficient to be

$$c_T^* = 2(F_{tot} - F_{tower})/u^2\rho A_{rotor} \quad (3)$$
$$c_T^* \approx 0.87. \quad (4)$$

Therewith, the thrust coefficient is the same for both turbines. We want to correct this is in the manuscript as follows:

p. 3, Table 1:

Table 1: Summary of main turbine characteristics. The tip speed ratio (TSR) is based on the free stream velocity u_{ref} at hub height. The Reynolds number at the blade tip, Re_{tip}, is based on the chord length at the blade tip and the effective velocity during turbine operation. The blockage corresponds to the ratio of the rotor's swept area to the wind tunnel's cross sectional area. The direction of rotation refers to observing the rotor from upstream, with (c)cw meaning (counter)clockwise. The thrust coefficients were measured at $\gamma = 0°$ and corrected for thrust on the tower and support structure..

Turbine	Rotor diameter	Hub diameter	Blockage	TSR	Re_{tip}	Rotation	c_T
ForWind	0.580 m	0.077 m	5.4 %	6	$\approx 6.4 \times 10^4$	cw	~~0.97~~0.87
NTNU	0.894 m	0.090 m	13 %	6	$\approx 1.1 \times 10^5$	ccw	0.87

p.11, l.20:

In [1], where the same setup was used, the skew angle for the NTNU rotor decreased from $x/D = 3$ to $x/D = 6$, which is a further indication for wall effects due to blockage, especially during yaw misalignment. Furthermore, both values show smaller angles as for the ForWind turbine. ~~In addition to the blockage effects, this is much likely caused by differences in thrust coefficient, cf. Table 1.~~

p.12, l.11:

As already seen in Figure 11, the wakes behind the ForWind turbine are deflected further and the curled shape is pronounced stronger, which can be attributed to ~~the larger thrust coefficient and~~ blockage effects. Figure 12(b) also shows that the wakes behind both turbines are slightly tilted. Looking at the black curves (ForWind turbine), an asymmetry can be noticed as the curves are tilted towards the left, while the red curves are tilted towards the right.

Barthelmie et al. report a thrust coefficient of $c_T \approx 0.8$ for Siemens 2.3-MW and 2.0MW Vestas V80 turbines. Trujillo et al. show a c_T of 0.77 for Adwen AD 5- 116 turbines, formerly called M5000-116. This list shows a bit more quantitatively, that a value of 0.87 is slightly high, although the theoretical optimum is at $c_T = 8/9 \approx 0.89$ [3]. When discussing the effect on our observations, one has to distinguish between

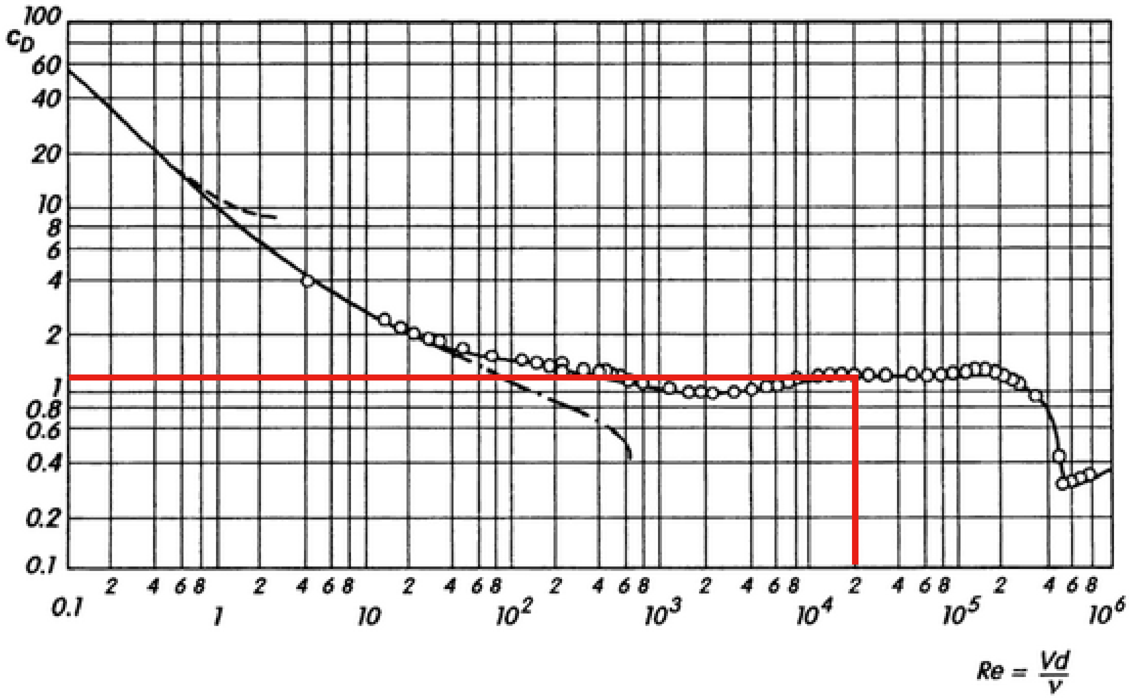

Fig. 1.12. Circular cylinder: drag coefficient vs. Reynolds number

∘	measurements by C. Wieselsberger, see H. Schlichting (1982), p. 17
- - - - -	asymptotic formula for Re $\to$ 0: $c_D = \frac{8\pi}{\text{Re}}[\triangle - 0.87 \triangle^3 + \cdots]$, with $\triangle = [\ln(7.406/\text{Re})]^{-1}$, $\text{Re} = Vd/\nu$, $c_D = 2D/(\varrho V^2 bd)$
- · - · - ·	numerical results by A.E. Hamielec; J.D. Raal (1969) and B. Fornberg (1985) for steady flow
Re = 300:	steady: $c_D = 0.729$, after B. Fornberg (1985)
	unsteady: $c_D = 1.32$, after R. Franke; B. Schönung (1988)

Figure 1. Screenshot taken from [2], drag coefficient over Reynolds number for a circular cylinder.

the different findings as done below:

Curles wake during yaw misalignment:

Two further experimental studies report on a curled wake shape during yaw misalignment. Bastankhah & Porté Agel [4] use a small turbine model of $c_T = 0.82$, while Howland et al. [5] use a drag disc of $c_T = 0.75$. Similarly, Berdowski et al. [6] simulated an actuator disc of $c_T = 0.89$. All three studies report the same general effect of a curled wake shape during yaw misalignment. Thus we think, qualitatively the effect does not depend on the thrust coefficient significantly.

Areas of high λ^2 values surrounding the vel. deficit:

To our knowledge, the ring of intermittent flow structures surrounding a velocity deficit of a wind turbine's wake as shown in Figure 7 of the manuscript, has not been reported before. Therefore, the effect of different thrust coefficients is hard to predict. However, speculating that the picture of the origin as described in the discussion section (p. 14, ll. 9-13) is correct, I would suspect a variation of the thrust coefficient would not affect the qualitative effect significantly. Of course the thrust has to be high enough to create a wake in the first place. In fact, during yaw misalignment the thrust in main flow direction is decreased and we do observe the same effect there, which supports the above speculation.

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3)

Blockage. Referred paper on tunnel effects refers to blockage correction (to correct free stream velocity and modify power and loads). Does the same conclusion hold for measured wake velocities or are they more sensitive to tunnel effects? Is there an influence of the asymmetry of the test section on the measured wake shape at 6D in yaw?

Thank you for the comment. We assume the referred paper on wind tunnel effects is Chen and Liou (2011) [7]. Unfortunately, it is not really clear which conclusion is meant in the referee comment, we assume the assumption of neglect-able blockage effects for a cross-sectional blockage ratio of $\leq 10\%$ is meant here.
We do believe that our results support the assumption of 10% blockage ratio being a good estimation for neglect-able blockage effects, even for wake velocity measurements 6D downstream. Figures 5 and 11 of the manuscript do not show any speed up effects behind the ForWind turbine (ratio $< 10\%$), which are visible behind the NTNU turbine (ratio $> 10\%$). Further, the wake center position based on the approach described in Section 2.2 of the manuscript result in symmetric values for positive and negative angles of yaw misalignment and slightly asymmetric values for the NTNU turbine. Thus, we conclude that the suggested 10% is a good estimation of blockage effects becoming noticeable. We stated this in the result (p. 7, ll. 26-27) and in the conclusions (p. 15, ll. 25-27) of the manuscript, however we suggest to reformulate more clearly:

p.15, ll.25 ff:
Minor differences could be ascribed to the more prominent blockage (12.8% vs 5.4%) in the NTNU setup, confirming findings by Chen et al. [7] even for wake velocity measurements, who state blockage effects can be neglected for a blockage ratio $\leq 10\,\%$.

We assume that 'asymmetric test section' refers to the test section having different extensions in y than in z direction. We believe that during yaw misalignment and the resulting wake deflection in z direction, the tunnel width (z direction) is the parameter potentially affecting the wake extension, especially for the larger rotor as previously discussed. For both directions, larger measures would be of advantage, however, we do not believe that both extensions being asymmetric cause specific effects.

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4)
2.1 pp3 Please state the cause/reason for the different TI. How was the homogeniety verified, do I understand correctly that standard deviation of flow velocity was the same in all three directions??

We certainly agree that the difference in TI is well worth discussing, thank you very much for pointing it out. The reasons for the different values in inflow turbulence intensity are wind tunnel limitations, unfortunately. The same turbulence grid at the test section inlet was used for both turbines. However, at first, the stream wise position of the smaller ForWind turbine was chosen as a compromise of two aspect: on the one hand, the position should be at a sufficiently large distance from the turbulence grid to allow turbulent mixing. On the other hand, the position should enable a traversing of the LDA system 6 rotor diameters downstream of the turbine.
As the NTNU rotor is larger than the ForWind rotor, the NTNU turbine had to be installed closer to the turbulence grid and therewith to the inlet to the test section, to allow wake measurements 6 rotor diameters downstream of the turbine in the test section of 11.15 m length. The traversing system in the NTNU wind tunnel is permanently installed, so moving the turbine was the only way to access downstream distances of 6D. Consequently, the grid generated turbulence did not decay to the same extent as for the ForWind turbine, unfortunately resulting in different turbulence intensities in the inflow.
Figure 2 of this document shows the resulting values of turbulence intensities,

$$TI := \sigma_u / \langle u \rangle \ , \tag{5}$$

over height, measured at a vertical line at the respective turbine's position, without the turbine being installed. Vertically, deviations in TI are within ±1.7% for the ForWind turbine and within ±3% for the NTNU turbine. Equation 5 states that only the stream wise flow component u was used, as not all three flow components were recorded.

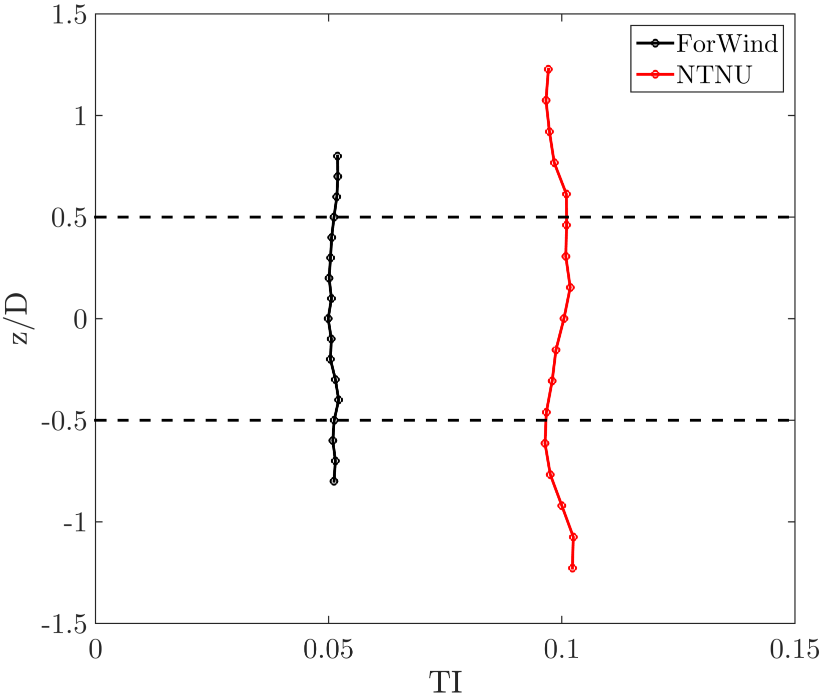

Figure 2. Turbulence intensity (TI) of the inflow for both turbines, measured in one vertical line at the turbine position without the turbine being installed.

We suggest to add the information about the turbulence intensity to the caption of Table 1 of the manuscript:

p.3, ll. 16 ff:
For the NTNU turbine, the reference velocity measured in the empty wind tunnel was $u_{ref,NTNU} = 10\,ms^{-1}$ *at a turbulence intensity of* $TI = \sigma_u/\langle u \rangle = 0.1$. *For the ForWind turbine, the inflow velocity was* $u_{ref,ForWind} = 7.5\,ms^{-1}$ *and* $TI = 0.05$. *In both cases,* ~~*the inflow*~~ *u(t) was homogeneous within* $\pm 6\,\%$ *and the TI within* $\pm 3\%$ *on a vertical line at the turbine's position.*

5)
2.2 pp4 motivate choice for x/D=6
Thank you for this comment. As previously mentioned in the answer to comment #4), six rotor rotor diameters is the upper limit that can be realized at the wind tunnel facility, setting the upper boundary of possible downstream distances. Within the project, we decided to measure two downstream positions to get an insight in downstream wake development. As 6D is the upper limit we chose this distance along with 3D as second distance, which was investigated in previous studies using a comparable setup [8, 9]. This manuscript here focuses on the comparison of 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) as comparing data of 2 turbines, 3 yaw angles, 2 distances and multiple inflow conditions would be too much for one manuscript. In the companion paper (Bartl et al. 2018 [10]), only one turbine was investigated, however, during different inflow conditions and both downstream distances.

wind farm	Horns Rev 1	Rødsand	Lillgrund	North Hoyle	Nysted
spacing [D]	7	5.2–7.8	3.3–4.4	4.4–10	5.8–10.4

Table 2: Overview of wind farm spacings as stated in [11].

The study by Walker et al. (2016) [11] uses measurement data from five offshore wind farms: Horns Rev 1, Rødsand II, Lillgrund, North Hoyle and Nysted, listed in Table 2. Averaging all values results in $\approx 6.47\,D$ as average turbine spacing. We thus conclude that the (somewhat forced) choice of 6D is a downstream distance relevant to consider.

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6)

5 pp15, does blockage also depend on Ct?

In this study, we did not investigate how varying the thrust coefficient affects blockage effects on the wake velocities. In our opinion, it would be very hard to isolate the effect of c_T on the blockage effect as varying the c_T would affect the wakes regardless of blockage effect. One study examining blockage effects during wind tunnel experiments using model wind turbines is Chen and Liou (2011) [7], although the focus is on turbine performance rather than wake measurements. Nevertheless, Figure 3 of this document shows that blockage effects (on performance) are dependent on the tip speed ratio. Thus, the c_T should impact blockage effects on performance.

> **4. Conclusions**
>
> This research provides quantitative results for the effects of tunnel blockage on the power coefficients of small horizontal-axis wind turbines in wind tunnel tests under different tip speed ratios (TSR), rotor pitch angles (β), tunnel blockage ratios (BR), and air freestream velocities (U_∞). Results indicate that the tunnel blockage effects and, thus, the blockage factor (BF) are largely dependent on TSR, BR, and β, and weakly dependent on U_∞. The blockage effects increase as TSR and BR increase, and as β decreases. The

Figure 3. Screen shot taken from [7].

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7)

5 pp15 It is stated that another paper "Bartl, J., Mühle, F., Schottler, J., Sætran, L., Peinke, J., Adaramola, M., and Hölling, M.: Experiments on wind turbine wakes in yaw: Effects of inflow turbulence and shear, Wind Energy Science, submitted, 2017." discusses the effect of inflow TI. " Since the differences between the measurements on the 2 turbines are discussed in the conclusions, what would be the effect of the different inflow TI for the 2 campaigns on the measured differences?

Thank you very much for this constructive point. I think to answer this question, one has to distinguish between the different findings/distinctions and discuss them separately as done below:

WAKE DEFLECTION

The manuscript reports different wake deflection magnitudes for both turbines (cf. Table 2 of the manuscript). The companion paper Bartl et al. (2018) [10] discusses differences in the wakes during yaw misalignment for the NTNU turbine and turbulence intensities of about 0.23% and 10%. Figure 4 shows the wakes behind the NTNU turbine for both angles of yaw misalignment and both turbulence intensities. [10] shows detailed elaboration on the differences, some of which I summarize here

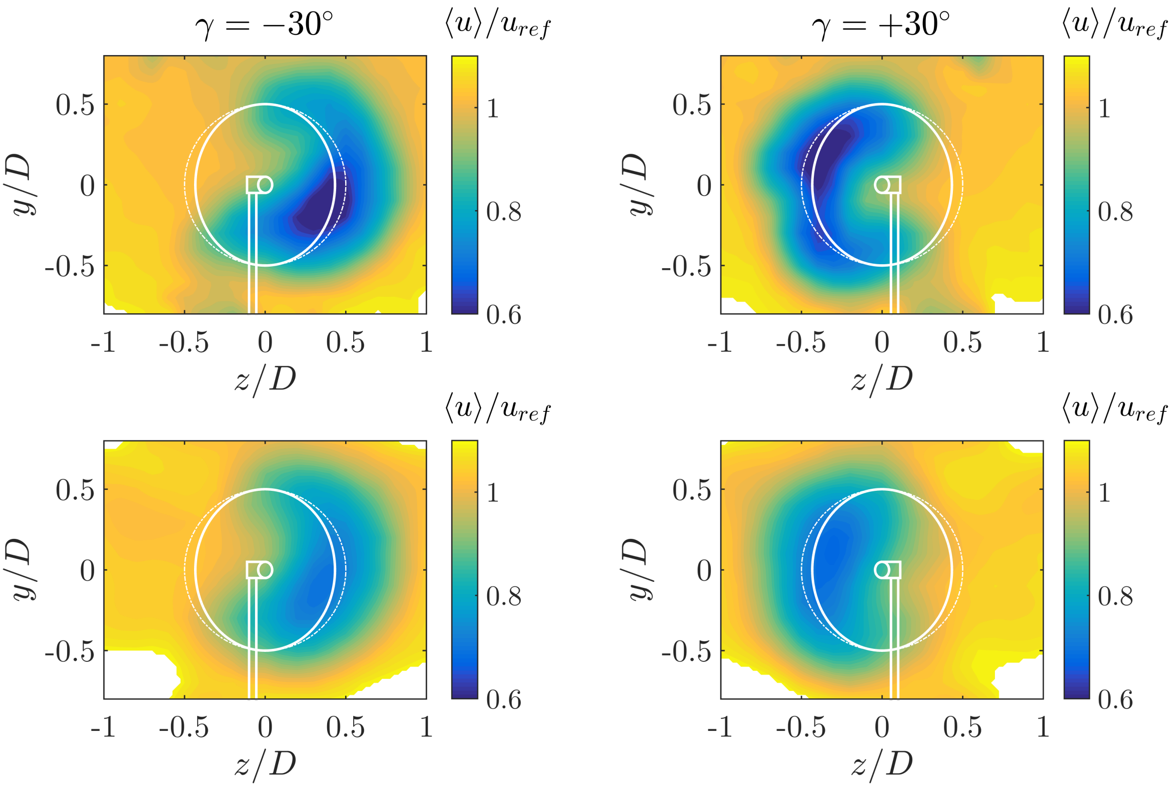

Figure 4. $\langle u\rangle/u_{ref}$ behind the NTNU turbine at $x/D = 6$. Left column: $\gamma = -30°$, right column: $\gamma = +30°$. Top row: inflow TI = 0.23%, bottom row: inflow TI = 10.0%. The same data was used in [10].

with regard to the referee comment.

In [10], we apply the same method for wake center detection as described in the manuscript. Figure 5 of this document shows a screen shot taken from [10], comparing the wake deflection magnitudes for different inflow conditions, inflow A and B being 0.23% and 10% inflow TI. As further discussed in the companion paper, the different inflows show only very small distinctions regarding wake deflection.

Further, the maximum velocity deficit is pronounced much stronger at low inflow turbulence. This is expected since higher TI enhances turbulent mixing with the free stream and thus wake recovery. Next, the (curled) wake shape appears to be more 'stable'/defined with higher TI. In my opinion, this effect is due to the *very* low TI of 0.23% (top row), and similar distinctions would not be observable comparing 5% and 10% inflow TI using the same turbine. In fact, the result of this manuscript do show a rather smooth shape for both turbines and thus both inflow TI values.

We suggest to point the reader's attention to the companion paper regarding the issue of 2 different inflow TIs by adding to the discussion of the manuscript:

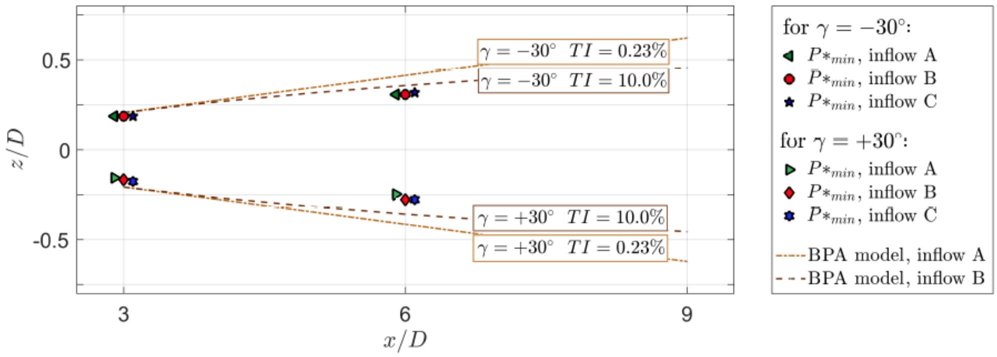

Figure 9. Calculated wake deflection $\delta(z/D)$ at x/D=3 and x/D=6 for three different inflow conditions A, B and C compared to TI-dependent deflection predictions by Bastankhah and Porte-Agél's wake deflection model. Note that a small offset in x/D of the measured values was chosen for better visibility.

Figure 5. Screenshot taken from [10], showing the wake deflection for different in flow conditions.

p.15, 20.ff:
This confirms findings by [12] and [9], reporting an asymmetric power output of a two-turbine case with respect to the upstream turbine's angle of yaw misalignment. *One should bear in mind that the inflow turbulence intensities are different regarding both turbines. We want to point out that the influence of inflow turbulence on the wake deflection is studied in [10], showing no significant effects.*

Ring of high λ^2 values

Regarding the ring of high λ^2, we see a strong influence of the free stream TI on the magnitude of λ^2 values. As can be seen in Figure 7 of the manuscript, the λ^2 values within the ring are considerably higher behind the ForWind turbine and thus for lower free stream turbulence. This connection is further supported by Figure 6 of this document, showing λ^2 contours behind the NTNU turbine for two different inflow conditions (TI=0.23% and TI=10.0%). Notice that the scale is different in both cases, showing that the values of λ^2 are higher for the low turbulent case, thus supporting the previous statement. Based on those two comparisons, we assume that a larger gradient in TI (or TKE) between wake and free stream leads to higher λ^2 values and thus more heavy-tailed increment PDFs on scales comparable to the rotor. This also fits to our interpretation that the ring of high λ^2 values arises from a transition zone, switching between wake state and free stream state, please see p. 14 ll. 9-12 of the manuscript.

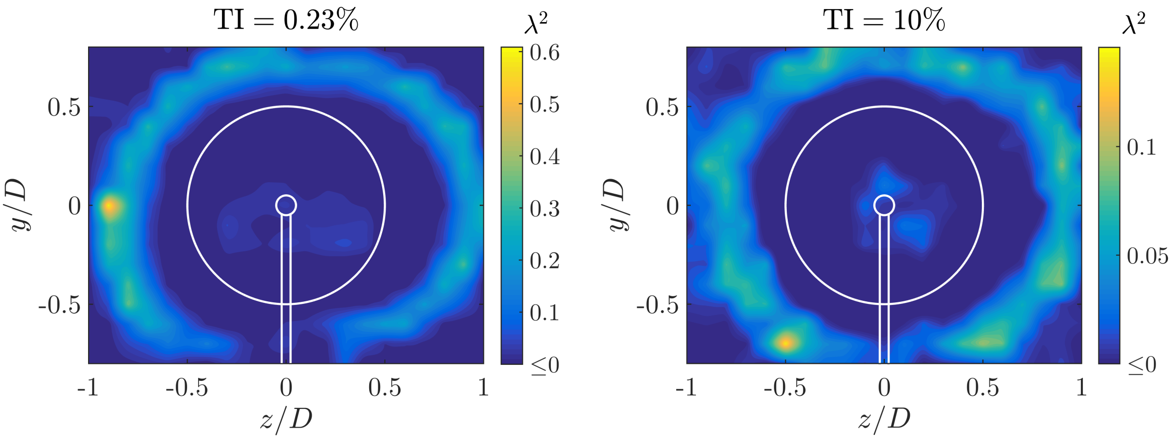

Figure 6. Shape parameter λ^2 at $x/D = 6$ behind the NTNU turbine. Left: free stream TI=0.23%, right: free stream TI=10.0%.

References

[1] Schottler, J., Mühle, F., Bartl, J., Peinke, J., Adaramola, M. S., Sætran, L., and Hölling, M., "Comparative study on the wake deflection behind yawed wind turbine models," *Journal of Physics: Conference Series*, Vol. 854, may 2017, pp. 012032.

[2] Schlichting, H. and Gersten, K., *Boundary-Layer Theory*, Vol. 102, Springer Berlin Heidelberg, Berlin, Heidelberg, 2017.

[3] Manwell, J. F., McGowan, J. G., and Rogers, A. L., *Wind energy explained: theory, design and application*, 2009.

[4] Bastankhah, M. and Porté-Agel, F., "Experimental and theoretical study of wind turbine wakes in yawed conditions," *Journal of Fluid Mechanics*, Vol. 806, No. 1, nov 2016, pp. 506–541.

[5] Howland, M. F., Bossuyt, J., Martínez-Tossas, L. A., Meyers, J., and Meneveau, C., "Wake structure in actuator disk models of wind turbines in yaw under uniform inflow conditions," *Journal of Renewable and Sustainable Energy*, Vol. 8, No. 4, 2016.

[6] Berdowski, T., "Three-Dimensional Free-Wake Vortex Simulations of an Actuator Disc in Yaw and Tilt," *2018 Wind Energy Symposium*, No. January, American Institute of Aeronautics and Astronautics, Reston, Virginia, jan 2018.

[7] Chen, T. and Liou, L., "Blockage corrections in wind tunnel tests of small horizontal-axis wind turbines," *Experimental Thermal and Fluid Science*, Vol. 35, No. 3, apr 2011, pp. 565–569.

[8] Schottler, J., Hölling, A., Peinke, J., and Hölling, M., "Wind tunnel tests on controllable model wind turbines in yaw," *34th Wind Energy Symposium*, , No. January, 2016, pp. 1523.

[9] Schottler, J., Hölling, A., Peinke, J., and Hölling, M., "Brief Communication : On the influence of vertical wind shear on the combined power output of two model wind turbines in yaw," , No. 2016, 2017, pp. 1–5.

[10] Bartl, J., Mühle, F., Schottler, J., Sætran, L., Peinke, J., Adaramola, M., and Hölling, M., "Wind tunnel experiments on wind turbine wakes in yaw: Effects of inflow turbulence and shear," *Wind Energy Science Discussions*, , No. January, jan 2018, pp. 1–22.

[11] Walker, K., Adams, N., Gribben, B., Gellatly, B., Nygaard, N. G., Henderson, A., Marchante Jimémez, M., Schmidt, S. R., Rodriguez Ruiz, J., Paredes, D., Harrington, G., Connell, N., Peronne, O., Cordoba, M., Housley, P., Cussons, R., Håkansson, M., Knauer, A., and Maguire, E., "An evaluation of the predictive accuracy of wake effects models for offshore wind farms," *Wind Energy*, Vol. 19, No. 5, may 2016, pp. 979–996.

[12] Fleming, P., Gebraad, P. M., Lee, S., Wingerden, J.-W., Johnson, K., Churchfield, M., Michalakes, J., Spalart, P., and Moriarty, P., "Simulation comparison of wake mitigation control strategies for a two-turbine case," *Wind Energy*, 2014.