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General Response

Thank you for this paper. It is very useful to receive experimental results, and it is always a major undertaking to gather such data. In general the paper is well written with good and useful figures.

My major criticism/suggestion is that the results presented in sections 3/4 are of too little data, and with too many "black box" issues to be used to draw conclusions from. Section 5 on the other hand provides results which are useful, line up with physical interpretation, and show statistical significance. I would therefore propose to condense (or remove?) sections 3/4, and perhaps expand a bit on section 5.

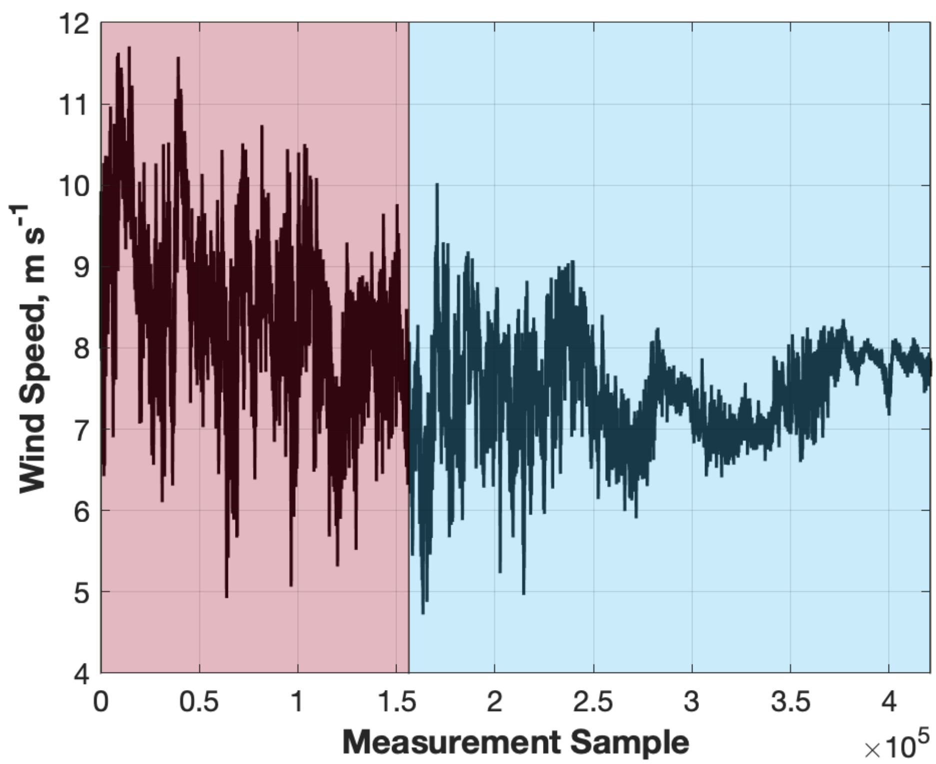
Thank you for your comments and the time taken to provide this review. The authors are glad you appreciate the experimental data and are understanding of the difficulties inherent to data collection.

The main criticism of the referee is that the results presented in Sections 3 (Wind Plant Control Experimental Setup, Controller Assessment, and Controller Assessment Challenges) and 4 (Measuring Wind Turbine Wake Response to First-Order Turbine Control Changes) are of too little data and with too many "black box" issues to draw conclusions from. The authors agree there are innate limitations to the dataset. However, this is why the initial focus of the manuscript was modified as analyses progressed to, in part, exploring the difficulties associated with performing a wind plant control experiment at full scale.

At the time of the experiment (14 December 2014), experimental validation of wind plant control at full scale was rare. Similarly, there was a dearth of observational data (especially compared to numerical simulation) characterizing in three-dimensions wind turbine wake structure and variability. Therefore, in collaboration with an industry partner, the preliminary objectives of the experiment were to (1) examine three-dimensional wind turbine wake response to changes in wind turbine yaw and blade pitch and (2) examine how these changes impact the net power production of individual turbines in the wind plant (i.e. quantifying the effectiveness of the wind plant control strategy). However, experimental logistics (e.g. experimental control limitations imposed by the wind plant operator) ultimately inhibited the successful execution of these experimental objectives. As noted in our response to referee one, the wind plant control experiment would have been ideally performed in an environment more conducive to the effectiveness of the implemented control strategies and for longer experimental durations. Still, the authors are confident that there is value to disseminating the results of this experimental campaign, albeit in a suboptimal environment and subject to innate limitations.

The results of this study lend insight into the complexities associated with performing a wind plant control experiment at full scale, and therefore, should be used to inform future field campaigns. Section 3 provides methods that can be referenced in future studies, but furthermore, this section highlights the importance of several key data sources and how not having access to these data can severely impact both analyses potential and the ultimate success of the field campaign. Section 4 additionally establishes that strategic yaw error in some ABL environments might not be sufficient to ensure effective wake steering. The authors were not intending based off this analysis to provide a statistical characterization of the wake. Rather, the authors are optimistic these results will promote further research examining how certain ABL conditions and transient ABL heterogeneities might impact both the effectiveness and potential benefit of various wind plant control strategies.

The results of Section 4 also provide a smooth transition to Section 5 (ABL stability driven wake changes). The referee suggests that the analysis in Section 5 should be expanded. Although this is desirable, SD wake analysis was also limited. For example, referee one advised that velocity deficits between the convective and stable ABLs be examined. However, analysis and comparison of the convective and stable ABL wake deficit profiles were hindered by several factors. First, there were significant differences in the turbine inflow wind speed between the convective and stable ABLs (reflected in Fig. 15 [now Fig. 16] using 10-min average data). Although 10-min average wind speeds were provided in the manuscript, high-temporal resolution wind speed data spanning the SD analysis period is provided in the figure below to demonstrate these differences in wind speed. The red and blue shaded regions denote the convective and stable portions of the SD acquisition period, respectively. The amount of momentum extracted from the inflow, and therefore the wake deficits immediately downstream, inversely vary as a function of the turbine inflow wind speed. Therefore, it would be difficult to exclusively attribute difference in the convective and stable wake deficit profiles to changes in ABL stability, rather than simply differences in the turbine inflow wind speed.



A second confounding factor to wake deficit analysis was the variation in measurement height with range (approximately 17.5 m per km moving away from the radar [noted in the manuscript on Pg. 5 Lns. 10 through 11]). This impacted the potential for wake deficit analysis as follows:

1) Wind shear varies between the convective and stable ABLs. In the stable ABL, wind shear is typically larger than in the convective ABL. Therefore, the turbine inflow wind speeds will be inherently larger than the wake velocities because of their relative measurement range and height. A shear-correction would be required to resolve relevant wake deficit profiles.

2) Because measurement height varies with range, different portions of the wake are being examined at incremental distances downstream.

For these reasons, it is difficult to know how relevant the extracted wake deficit profiles would be for research purposes, or how well they would correlate with wake deficits found in previous research. Wake length was instead examined as a proxy to discern the downstream extent of the wake effect in both the convective and stable ABLs.

Despite the inherent limitations of the datasets presented, the authors are confident they provide a valuable contribution to the scientific community by highlighting links between the ABL and wake structure and variability and how this might impact the effectiveness of wind plant control. Furthermore, exploring the difficulties associated with performing a wind plant control experiment at full scale should help improve future experimental design.

Specific Comments

P 2 "operate below their peak capacity to decrease wake effect..." this describes well static induction control, but less well wake steering and dynamic induction control

Thank you for your comment. The manuscript text was slightly modified to improve reader comprehension. The edited text is provided below.

Pg. 2 Lns. 12 through 14:

> “When wind plant control is employed, some turbines in the wind plant will modify their control settings (sometimes operating below their peak capacity) to decrease the wake effect, thereby increasing the plant-wide available kinetic energy (De-Prada-Gil et al., 2015).”

Fig 1: It’s explained later, but the legend is unclear in meaning, perhaps explain more in caption

Thank you for noting that the figure was not adequately described, the other reviewer shared a similar position. As you mention, the figure was initially detailed later on in the manuscript in Section 3 (Pg. 5 Lns. 11 through 16 and Pg. 6 Lns. 1 through 2). However, upon reconsideration, the authors recognize that this text is disconnected from the description of the 14 December 2014 deployment (i.e. Section 2.1) and Fig. 1. Therefore, this text was moved to Section 2 and was slightly modified to more comprehensively describe Fig. 1. The modified text is provided below.

Pg. 4 Lns. 14 through 23:

"Located in the DD domain of the 14 December 2014 deployment were 20 wind turbines distributed across two turbine rows. The wind turbines were characterized by a hub height of 80 m and a rotor diameter (RD) of 101 m. Supervisory control and data acquisition (SCADA) information detailing the turbine inflow wind speed (subject to the nacelle transfer function [NTF]), turbine yaw orientation, and blade pitch angle were provided at a one-hertz sampling frequency from 14:00:00 UTC to 16:59:45 UTC for seven of the wind turbines (denoted by the non-black circles in Fig. 1). Three of the seven wind turbines were located in the lead row of the wind plant (denoted by the blue, red, and purple circles in Fig. 1), while the remaining four were located in the trailing row (denoted by the white circles in Fig. 1). The three lead-row wind turbines were separated by an average distance of 1512.2 m (~15 RD) from the trailing turbine row and were laterally separated from each other by an average distance of 321.1 m (~3 RD). The wake of these three lead-row wind turbines (referred to as the T_L, T_T, and T_R) were analyzed to examine the effectiveness of the implemented wake-mitigating control strategies."

Furthermore, both the Fig. 1 caption and legend were modified to improve reader comprehension. The updated figure and revised caption are provided below.

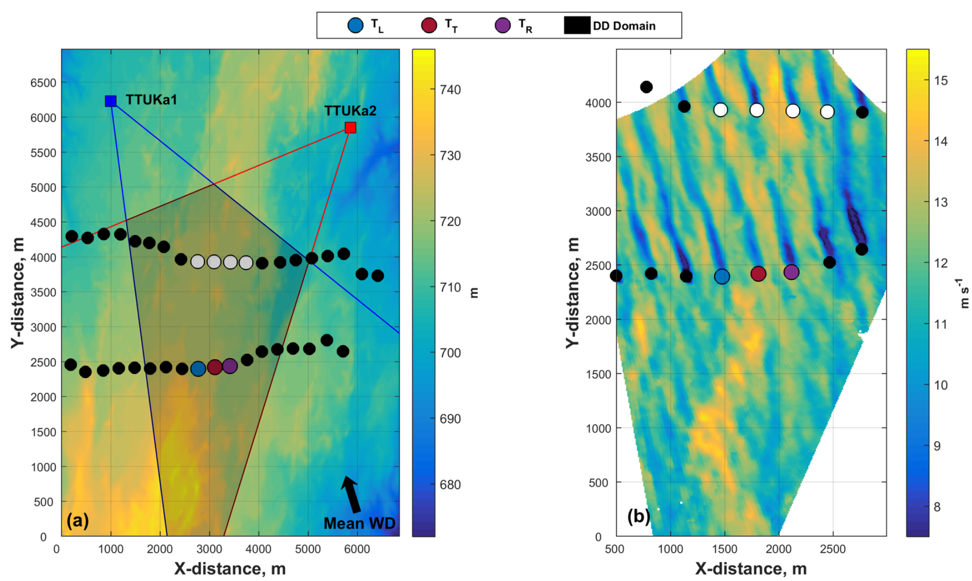


Figure 1. (a) Schematic of the TTUKa DD radar deployment on 14 December 2014 including radar deployment locations (red and blue squares), the radar sectors scanned (defined by the red and blue outlined regions), the DD domain (shaded black region), the location of the individual wind turbines (colored circles [the meaning of the different turbine colours are defined in Sect 2.1]), the mean wind direction (black arrow), and the underlying mean sea level elevation (m). (b) TTUKa DD hub-height wind speed (m s^{-1}) at 14:59:29 UTC overlaid by the wind turbine locations.

P6: RD?
RD is an acronym for rotor diameter and was established in the initial manuscript submission on Pg. 5 Lns. 12.

> "The wind turbines were characterized by a hub height of 80 m and a rotor diameter (RD) of 101 m."

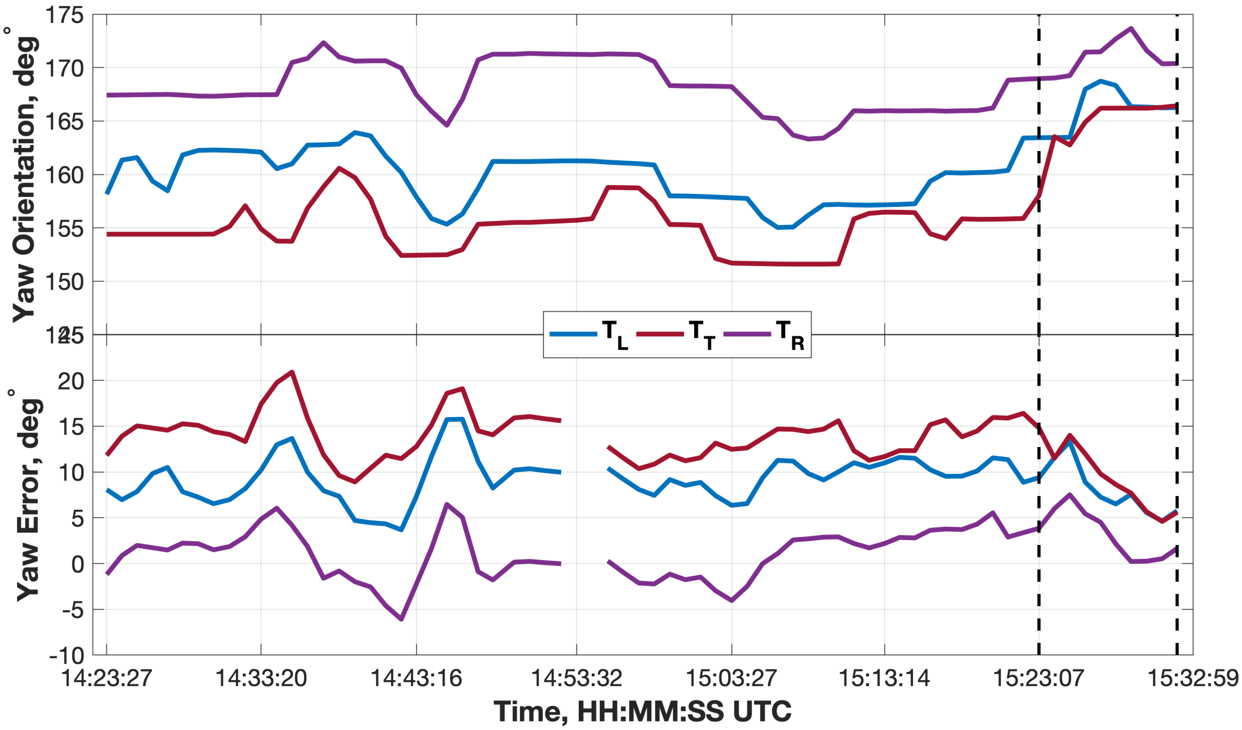
This manuscript text was shifted up as part of the changes made to Fig. 1. The authors can confirm that the acronym RD was pre-established prior to its use in the manuscript.

Bottom p9: Could alternatively define wind direction as the average yaw position of non-changed turbines?

Thank you for your input. The referee suggests that wind direction could be defined as the average yaw position of non-changed turbines as opposed to using the freestream wind direction (i.e. $\theta_{\mathrm{inf}}^{V}$). However, the authors believe that an average wind direction based on DD measurements in the upstream 1.45 km by 1.8 km freestream analysis area is more appropriate for analyses for several reasons. One reason for opting to use $\theta_{\mathrm{inf}}^{V}$ instead of the average yaw position of non-changed turbines is the timescales of interest in the manuscript. Wake deflection is examined on a volume-by-volume basis, or approximately at 60-s time intervals consistent with the DD volume acquisition period (i.e. 60.4 s). Therefore, to ensure the robustness of the results, the wind direction estimate used to define wake deflection should be determined at similar time intervals (i.e. $\leq$ 60.4 s). While the average yaw position of the non-changed turbines could be determined at these timescales, they are not expected to provide a more accurate estimate of the turbine inflow wind direction because of the construct of the wind turbine yaw controller. Refer to Pg. 9 Lns. 6 through 8 of the initial manuscript submission:

> "Unlike the construct of the blade pitch controller, a wind turbine will not actively yaw on a second-by-second basis to ensure optimal rotor alignment. A wind turbine will typically only yaw when the yaw error has exceeded some threshold (e.g. $\pm$10°) for an extended period of time (e.g. 10 min)."

Therefore, as long as the yaw error does not exceed this pre-established threshold, the wind turbine will not modify its yaw to be better aligned with the inflow. While at larger timescales the wind turbine might be expected to exhibit little to no yaw error, this is not true for the minute timescales used in the presented wake deflection analysis (as demonstrated in the figure below). Provided in the top subplot is a time history of the T_L, T_T, and T_R yaw orientation angles and provided in the bottom subplot is a time history of the T_L, T_T, and T_R yaw error angles (i.e. $\theta_{\mathrm{err}}^{V}$) as defined relative to $\theta_{\mathrm{inf}}^{V}$. The vertical dashed lines denote the temporal bounds of the +10° experimental period (i.e. 15:22:00 UTC – 15:31:59 UTC). Despite the T_L, T_T, and T_R yaw controller remaining unmodified between 14:22:32 UTC and 15:22:00 UTC, each turbine exhibited significantly different yaw orientation angles. During this period wherein no turbine yaw changes were implemented, the T_L exhibited a mean yaw orientation angle of 160.6°, the T_T exhibited a mean yaw orientation angle of 156.4°, and the T_R exhibited a mean yaw orientation angle of 168.5°.



Considering each turbine exhibits yaw error (and a wide range of yaw error values at that) in this period, the authors do not believe using the average yaw position of ‘non-changed’ turbines is more appropriate than using $\theta_{\mathrm{inf}}^{V}$ to define the yaw deflection angles.

Fig 8: Believe these wake directions are convex in the wrong direction, the wake deflection appears to be accelerating as heading downstream, whereas expectation would be recovery to main direction (cf fig 1 in Jiménez, Ángel, Antonio Crespo, and Emilio Migoya. “Application of a LES Technique to Characterize the Wake Deflection of a Wind Turbine in Yaw.” Wind Energy, 2010. https://doi.org/10.1002/we.) this might also impact analysis in fig 10.

The referee notes that Fig. 8 indicates wake deflection increases with distance downstream. This was not the intended interpretation of the figure, instead the figure was meant to denote the general wake deflection directions (i.e. right/left) when certain yaw error angles were present (i.e. positive/negative). This is why no units were placed on either the X or Y axis. However, the authors do recognize that the reader could easily misinterpret the figure. Therefore, the figure was modified to more accurately convey the intended message. The revised figure and caption are provided below.

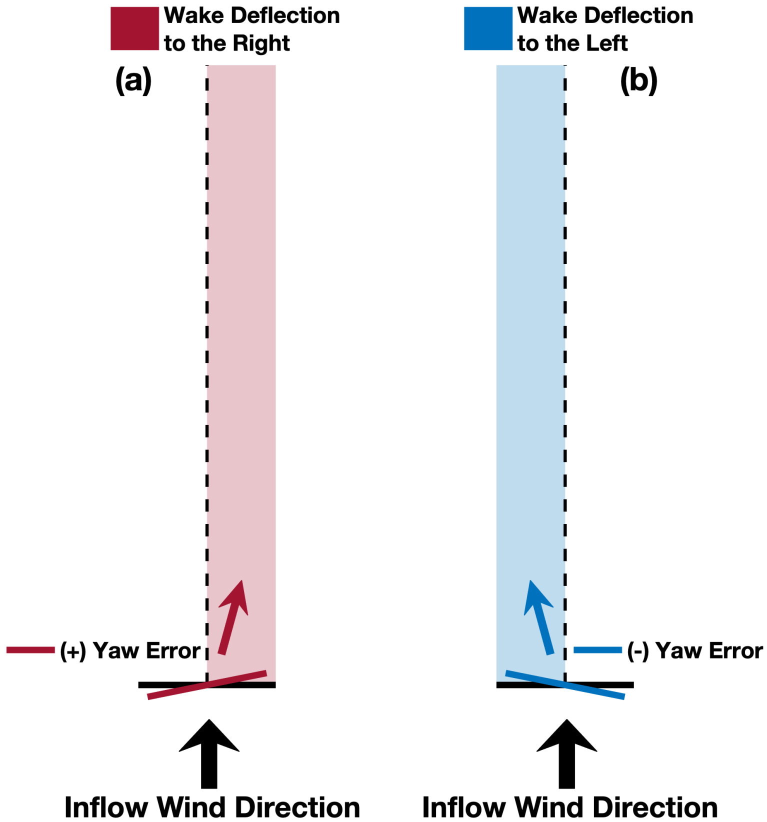
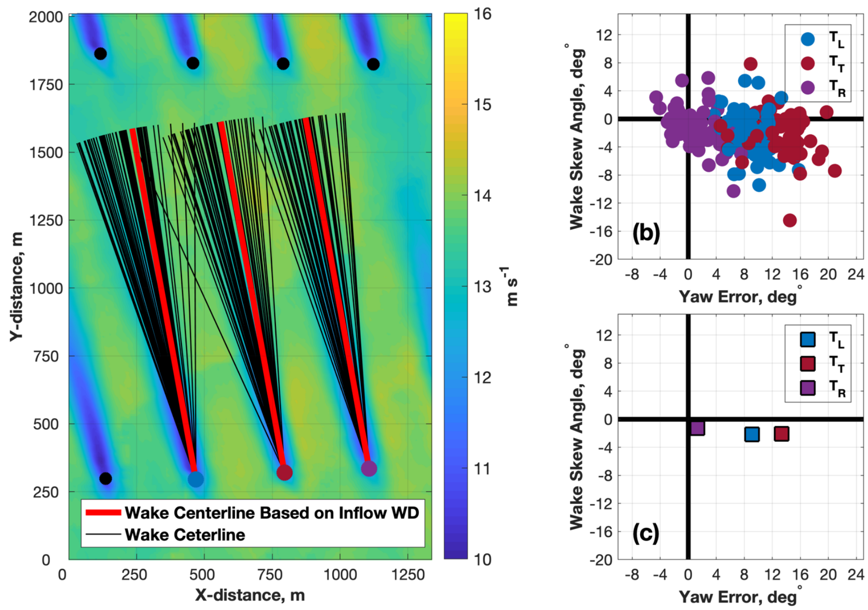


Figure 8. Wake deflection directions theoretically induced by (a) counterclockwise (i.e. $\theta_{\text{err}} > 0$) and (b) clockwise (i.e. $\theta_{\text{err}} < 0$) yaw rotation relative to a fixed turbine inflow wind direction.

The referee also correctly states that even though yaw error can promote wake deflection in a particular direction, this deflection angle will not continue infinitesimally downstream. At some downstream distance (as noted in Fig. 1 of Jiménez et al. [2010]), downstream wake progression will become more consistent with the governing wind direction. Although this is true, the authors are confident that this downstream wake behavior did not significantly impact the results presented in Fig. 10.

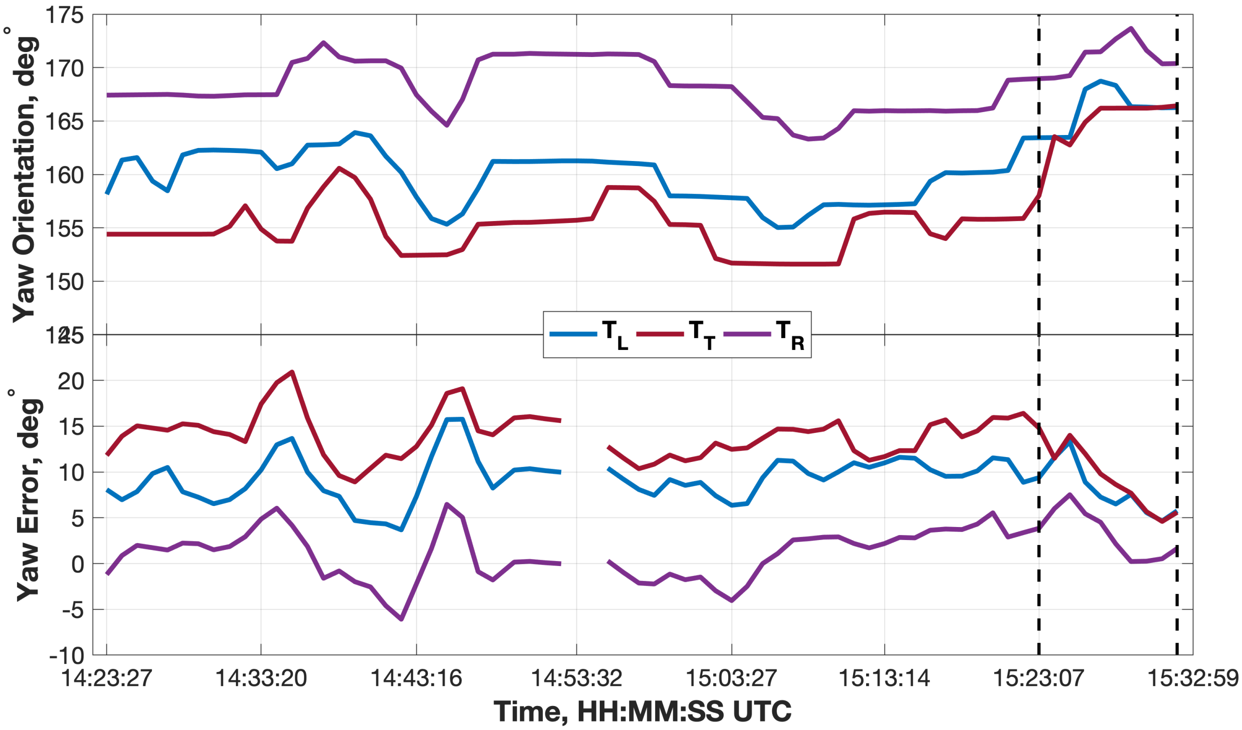
First, let the authors clarify that wake deflection was defined relative to θ^V_{inf} and not the pseudo-expected lines curves initially depicted in Fig. 8. Secondly, the aptitude of downstream wake progression to return to values consistent with the governing wind direction should slightly reduce the absolute value of the derived wake deflection angles (i.e. θ^V_{skew}). Therefore, had this downstream wake progression impacted results, it would also indicate that wake deflection in the near-wake region was likely more anomalous (i.e. further to the left) than that indicated by the mean T_L, T_T, and T_R values of θ^V_{skew}. Therefore, a return of the downstream wake progression to directions consistent with the mean flow would not have impacted the take-home message of the wake deflection analysis—the mean T_L, T_T, and T_R θ^V_{skew} values were opposite of that expected, indicating that some ABL characteristics (e.g. boundary layer streak orientation) might be instead governing wake orientation and downstream wake progression.

Regardless, the authors did consider the potential impact of downstream wake progression returning to directions consistent with the mean flow when performing analysis. For example, assume wake center locations outwards of only 6.5 RD downstream were considered (i.e. instead of the 13 RD used in the manuscript). Using only these wake centers to derive θ^{V}_{skew} results in the figure below (i.e. the same as Fig. 10 but using a different wake center distribution) and a mean T_L θ^{V}_{skew} value of -2.15°, a mean T_T θ^{V}_{skew} value of -2.06°, and a mean T_R θ^{V}_{skew} value of -1.27°. Therefore, these results indicate that for the downstream distances examined (i.e. 13 RD) any tendency for downstream wake progression to return to values consistent with the mean flow did not significantly impact the presented results.



P 19 "simply implementing yaw error might not be enough to ensure effective wake steering" not clear this result can be drawn from these results

Demonstrated in the figure below, both the T_L, T_T, and T_R exhibited yaw error in the DD analysis period. The DD analysis period mean θ^{V}_{err} value was positive for each turbine (refer to Fig. 6 of the manuscript), yet the mean θ^{V}_{skew} values were negative for each turbine in the DD analysis period. These negative θ^{V}_{skew} values are opposite of expected based on theory. Therefore, positive values of θ^{V}_{err} were not sufficient given the underlying ABL conditions to elicit the expected wake deflection to the right when looking downstream.



However, the authors note that the manuscript text does not adequately denote why simply implementing yaw error might not be sufficient to ensure effective wake steering. It is trivial given previous research to note that yaw-induced wake deflection is possible. However, it is not fully understood how the effectiveness of yaw-based wake steering varies given the prevailing ABL conditions. Therefore, the manuscript text was modified to indicate that in some ABLs (e.g. a convective ABL or in the presence of certain ABL heterogeneities such as ABL streaks) simply implementing yaw error might be sufficient to ensure effective wake steering.

Pg. 20 Lns. 10 through 13:

> "Regardless, these results are important because they suggest that in certain ABLs simply implementing yaw error might not be sufficient to ensure effective wake steering; rather, an integrated knowledge of ABL heterogeneities and their characteristics is needed (e.g. interaction with these transients might amplify or inhibit wake deflection)."

Fig 17 and Fig 20: Great figures and really interesting!! Text analysis also interesting

Thank you for your comment. The authors are glad that you found the analyses to be interesting.