In this document, the reviewer comments are in black, the authors responses are in red.

The authors thank the reviewer for their thoughtful and productive comments.

SUMMARY: This paper discusses the analyses of wind turbine wake structure considering varying atmospheric stability regimes using measurements from a single scanning lidar; representing an extension of the work of Aiken and Lundquist (JTECH, 2014). Frequency in wake detection, wake velocity deficits, wake width, and wake centerline results are presented. I found the discussion related to the wake stretching as a result of vertically veering wind direction to particularly interesting. The impact of atmospheric stability on wake behavior is a very important aspect to understanding wind plant performance as a whole, and as this paper shows there are significant and consistent (e.g. diurnal) changes in wake behavior as a result of the background stability. I believe the results of this paper are a meaningful contribution and worthy of publication, but I do have a few comments/questions requesting clarity for how the measurements are used to construct the analyses and what the downstream implications are for the presented results.

Thank you for finding our work interesting and useful!

MAJOR COMMENTS/QUESTIONS: While the title infers a 3D construction of the wakes for analysis, in reality, all of the presented wake statistics are only assessed from individual 2D planes. Since multiple elevation tilts are used, I would have liked to see the author construct fully integrated 3D volumes of data by interpolating the polar data from a given elevation series (by elevation series I mean a single collection of the six elevation tilts between 1.5-2.8 degrees) into a 3D Cartesian grid. Otherwise, when assessing wake deficit and width, how can we be certain that any given 2D plane is a complete representation of the absolute downwind wake deficit or wake width since that plane only represents a horizontal 2D "slice" somewhere through the wake?

You are right: single 2D plans cannot be considered as a full representation of wake characteristics. In fact, we considered data from PPI scans performed at all the six elevation angles to retrieve results for the velocity deficit and the wake width. As shown in Figure 2, we can in this way produce a representation of a considerable part of the whole wake region, at different altitudes and different downwind distances from the turbine.

Since deficits and widths were computed separately from the individual PPI elevation planes within the same elevation series, this would mean multiple wake deficit/width calculations for the same downwind distance exist within the same elevation series, but inherently represent different vertical locations within the wake. Or maybe the generated wake statistics for one elevation series are binned by range regardless of their height?

For the whole discussion of the velocity deficit and the wake width, all the different elevation angles of the PPI scans are included in the results: the focus for these two characteristics is mainly on how these change with downwind distance and how different relative position (i.e. inner vs outer wakes) affect the results.

Additional discussion on how the statistics from individual tilts within a single elevation series are merged (or not) would provide for a better understanding of the bulk wake statistics (e.g. deficit and width) and how representative the statistics are of the character of the full wake at any given downwind distance.

Thank you for noticing that our discussion about the different elevation angles was not clear. The revised manuscript will clearly state that all the six elevation angles are used to retrieve the results regarding wake width and velocity deficit: "during all the scans (at all the considered elevation angles) performed on 23 and 26 August 2013".

I apologize if I have misinterpreted the analysis, but I believe there needs to be further clarification of how the 2D planes of PPI data are used to generate the wake statistics, and what inherent assumptions/limitations are associated with the methods. I would also encourage the author, though not required, to consider analyzing the data in a true 3D framework when constructing the presented wake statistics.

Although we appreciate the suggestion of a full 3D framework retrieval of the wake structure, we think that the way we chose to present our results – now improved to better explain how we used different elevation angles – is more intuitive and similar to the presentation style of comparable results in the literature in this field (Aitken et al. 2014, Banta et al. 2015, among the others). Thus, we decided to keep our way to present the results; however, we thank the reviewer for their useful suggestion, which might be implemented in a future paper about the topic, possibly using data from different field campaigns.

MINOR COMMENTS/QUESTIONS:

1. P4, L8: What is the range from the WINDCUBE to the four turbines of interest? The distances can be inferred from Figure 2, but the numbers would be useful in the text.

The revised caption of Figure 2 will include the distances of the four considered turbines from the scanning lidar (2136 m, 2102 m, 2171 m, and 2286 m).

2. P 4, L 14: What is the scan speed of the lidar? What range of azimuths are scanned?

The scan speed of the lidar during a PPI scans was of 0.5deg/s. Each PPI scan spanned an azimuth range of 50deg. The revised manuscript will include the following sentence: "each PPI scan lasted approximately 100 seconds, spanning an azimuth range of 50 deg with a speed of 0.5 deg/s."

3. P4, L 19: How long does it take the lidar to scan the series of six elevation tilts?

The following table with a detailed description of the scan pattern – and its duration - used in the experiment will be included in the manuscript, along with an explicit statement that "Approximately ten minutes were required to collect the series of six elevation tilts":

Table 2. *Description of the 30-min cycle of scanning lidar scans in CWEX-13 field campaign. The characteristic fixed angle refers to the elevation angle for PPI and VAD scans, the azimuth angle for RHI scans.*

number of scans	type of scan	characteristic fixed angle	duration of each scan	cumulative time
2	VAD	75°, 60°	132 s	0:00 - 4:24
6	PPI	2.8°, 2.5°, 2.2°, 2.1°, 1.8°, 1.5°	104 s	4:24 - 14:48
3	RHI	160°, 170°, 180°	32 s	14:48 - 16:24
6	PPI	2.8°, 2.5°, 2.2°, 2.1°, 1.8°, 1.5°	104 s	16:24 - 26:48
6	RHI	160°, 170°, 180°, 180°, 170°, 160°	32 s	26:48 - 30:00

4. P9, L 11: This comment relates to the Major Comments/Questions section above. How is the ambient flow wind speed defined on the 2D PPI plane? Since the PPI plane is slanted, if the ambient flow wind speed is determined upstream of a given turbine, can you comment on the impact of using this value for constructing wake deficits downstream of the turbine, but at lower heights due to the slanted PPI plane? Is the comparison being made at different heights because the PPI plane is sloped? If so, what are the implications on the wake deficit calculations?

Thank you for pointing out that we did not specify which ambient flow speed we used for this calculation. The ambient flow wind speed is estimated (as one of the parameters of the used models) by our wake characterization algorithm at each range gate in each PPI scan. Thus, since we have a different value for each range gate, different vertical levels do not affect this calculation. To make this clear, we will rephrase the sentence as follows: "the ambient flow wind speed u (estimated from our algorithm at each performed fit at each range gate and elevation)".

5. P9, L30: How many scans are used to generate the statistics in Figure 5? Are all of the 438/576 scans performed on 23 Aug/26 Aug considered? Are all elevation tilts considered?

Yes, all the scans at all elevation angles are considered in this Figure. Thanks for pointing out that this had not been clearly stated in the text. The following sentence will be added to clarify this: "during all the 438/576 scans (at all the considered elevation angles) performed on 23/26 August 2013".

6. P10, L13: Does this statement imply that a single elevation series of six scans takes 11 minutes to complete? If so, that may answer Question 3 above.

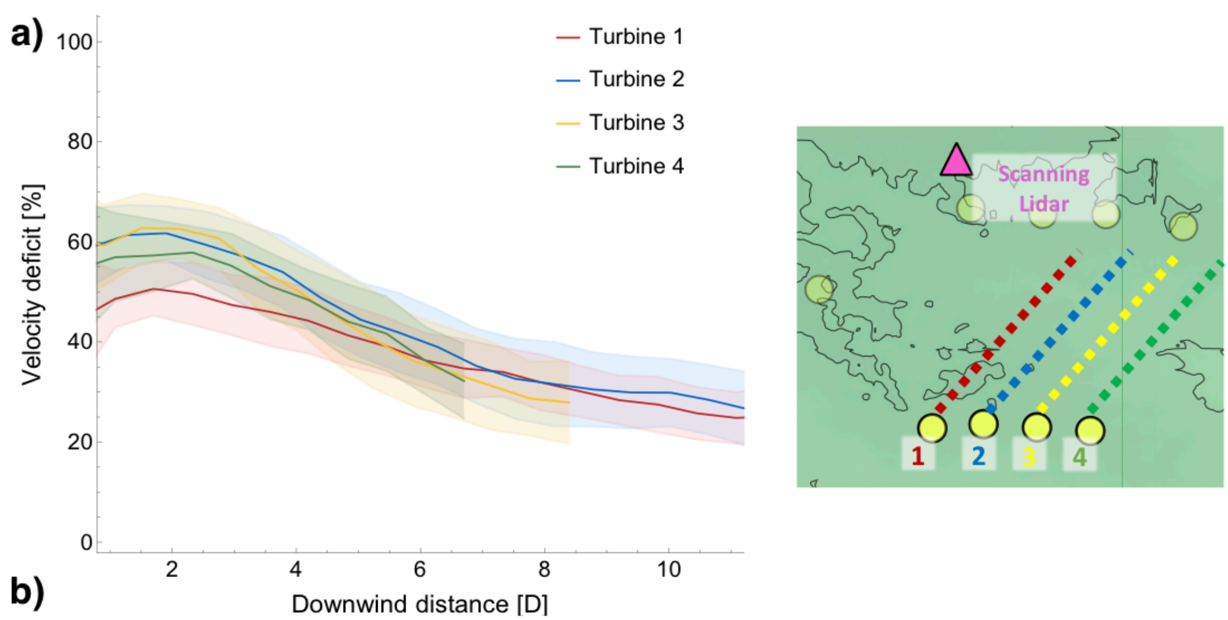
Yes it does. However, as stated above, the duration of the scans will be explicitly shown in a table in the revised manuscript.

7. P10, L18: While the difference in wake deficit between the inner and outer wakes is shown, can the author comment on the difference in wake deficit between the outer turbines, as that difference is actually more substantial? Which line is for which turbine? Assuming the wind direction is relatively consistent throughout (maybe a bad assumption), can a composite PPI image be provided corresponding with this period to highlight if there are any features in the flow (e.g. a turbine row edge effect) that could be contributing?

See our answer to the next comment below.

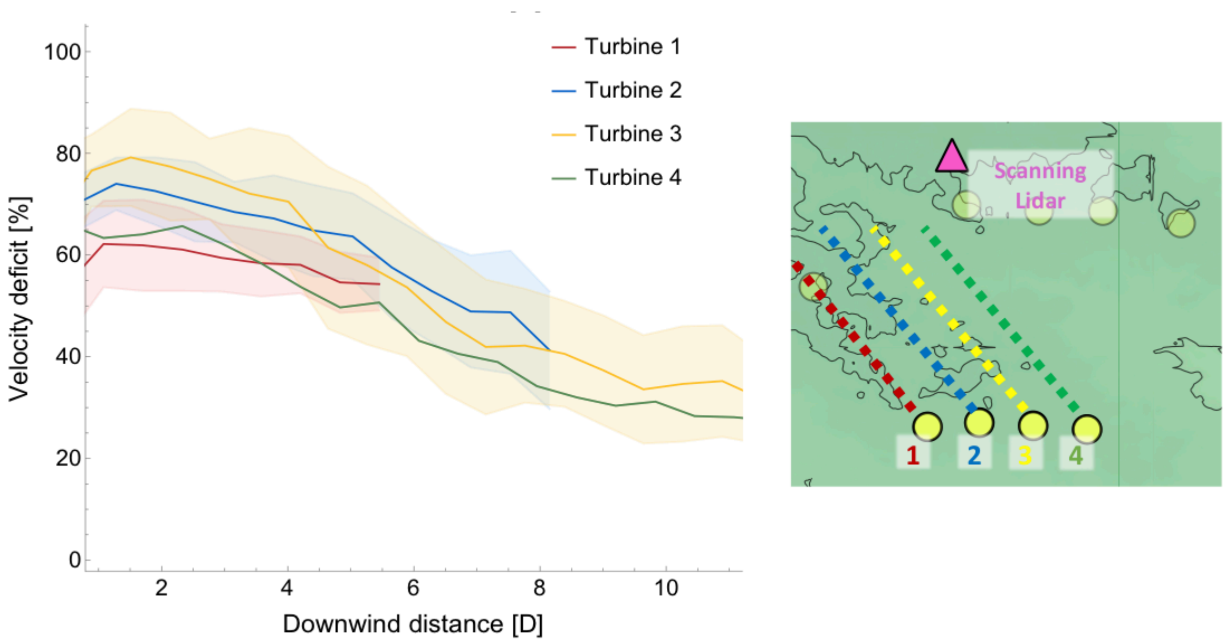
8. P12, L2: While the author states comparable results occur between the 23-August and 26-August cases, do the red lines, for example, flip with the different wind direction, again inferring some type of turbine row edge effect?

Thank you for your thoughts about this result. We will change our Figure to label the individual turbines, as follows:



The sketch on the right will also help the reader to remember the wind direction for the considered day.

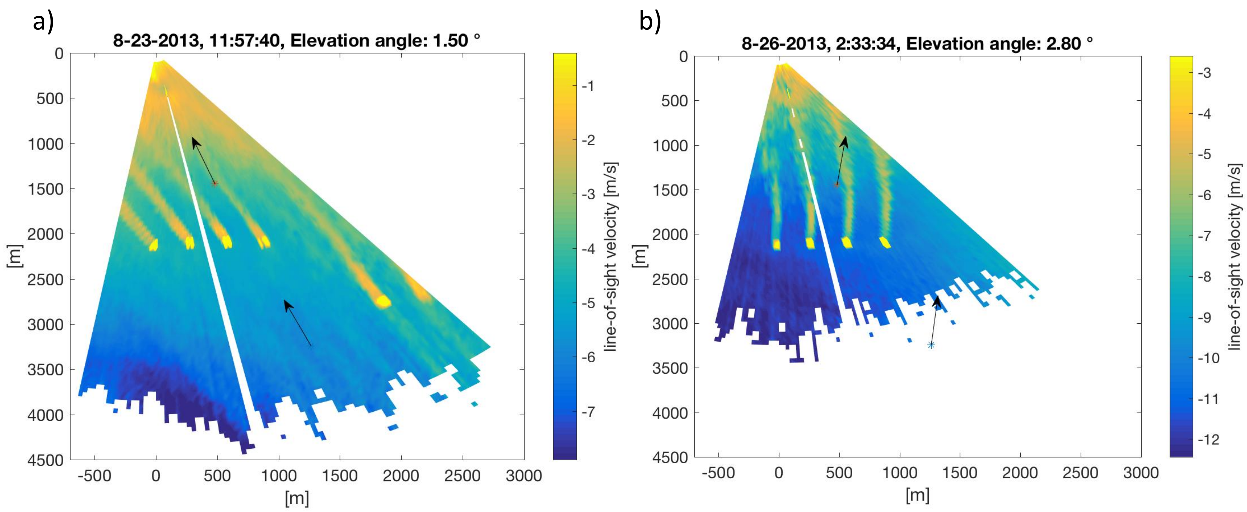
Thank you also for pointing out that our comparison between 23 and 26 August was not clear enough. To solve this issue, we will include the plot for 23 August (see below) in Figure 7, whose caption will be rephrased as: "Velocity deficit vs downwind distance, for the four wakes of the studied row of turbines. Continuous lines represent the median values calculated from the PPI scans performed at all the considered elevation angles during the night (stable conditions) of 26 (panel a) and 23 (panel b) August 2013".



As can be seen, for the 23 August 2013 the difference between outer (turbines 1 and 4) and inner (turbines 2 and 3) wakes is more consistent for all the studied turbines, and the difference between the velocity deficit for the two outer turbines (noticed by the reviewer for the 26 August case) is not present anymore. Therefore, we cannot infer general results for other flow features (e.g. edge effects) beyond what we stated in the paragraph: "wakes from outer turbines (number 1 and number 4), have lower velocity deficits than the wakes from inner turbines (number 2 and number 3), for relatively small downwind distances, with a difference up to 15%".

9. P12, L18: Could an example PPI image or composite be included to visually highlight the wind direction dependence on wake width detection being discussed here?

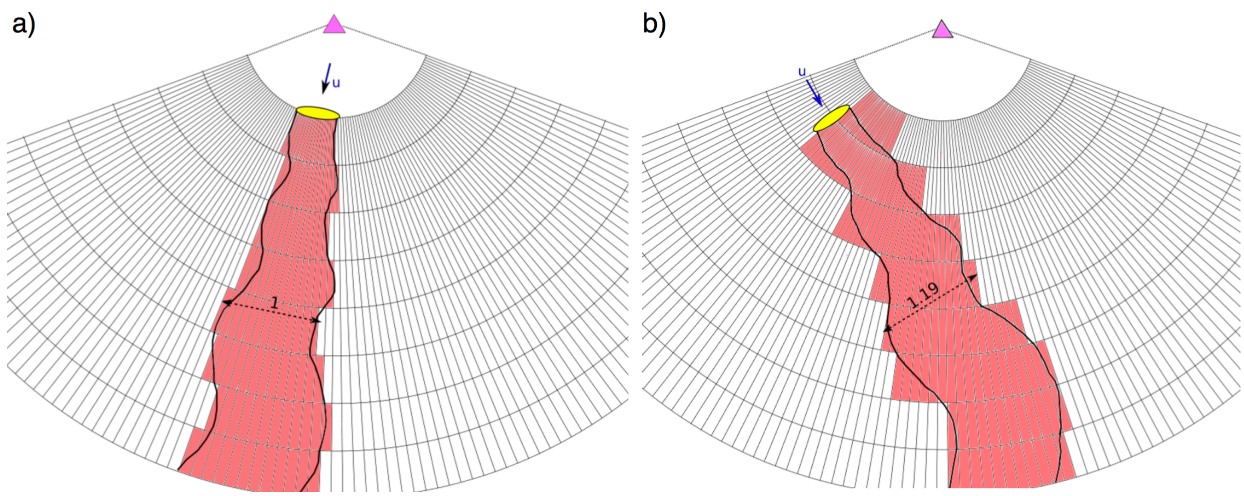
This dependence can be seen in the following two color-maps of the line-of-sight velocity measured in two PPI scans during 23 and 26 August, which will be included in the manuscript at the end of the "Lidar measurements" section:



The caption of the Figure will be: "Figure 3. Color maps of line-of-sight velocity measured by the scanning lidar during two PPI scans performed at 11:57 UTC (6:57 am LDT) on 23 August 2013 (panel a) and at 02:33 UTC (9:33 pm LDT) on 26 August 2013 (panel b). The scanning lidar is located in the origin of the coordinate system. The two arrows show wind direction as measured by the profiling lidars WC-1 and WC-2 at 80 m AGL."

Moreover, we will add the following paragraph and Figure to better explain our interpretation of this result:

"This result is due to the relationship between the viewing angle and the aspect ratio of the lidar retrieval "pixels", which are related to the relatively long range gate (50 m) and relatively narrow azimuthal resolution (0.5 degree). As qualitatively shown in the schematic of Figure 10, the scanning lidar measures the line-of-sight velocity in narrow pencil-shaped "pixels". With this geometry, if the wind direction - and thus the wake - is aligned with the line-of-sight from the lidar, the wake width can be assessed with high precision due to the high azimuthal resolution in each pencil-shaped area (panel a). However, if the wind direction - and thus the wake - is not aligned with the line-of-sight from the lidar (panel b), then the same wake will be measured as generally wider, since the retrieval of the wake width is now affected by the relatively coarse radial resolution of the lidar coordinate grid. In the schematic diagram shown in Figure 10, at an arbitrary fixed downwind distance from the turbine, the (same) wake would be detected as 19% larger when it is not aligned with the line-of-sight from the scanning lidar. This result becomes more evident the when the laser beam is more perpendicular to the wake. This result is due to the aspect ratio of the lidar "pixels," and thus would affect other wake characterization approaches relying on instruments not co-located with the turbine such as in Banta et al. (2015); Aitken et al. (2014a), but would not affect nacelle-mounted wake measurements, such as in Bingöl et al. (2010); Aitken and Lundquist (2014) as nacelle-mounted wake measurements are usually aligned with the wake, unless the wake is intentionally yawed (Fleming et al., 2016; Trujillo et al., 2016)."



"Figure 10. Qualitative sketch of the dependence of detected wake width on the orientation of the coordinate grid used by a scanning lidar (purple triangle) as a function of the wind direction. Panel a shows the case of a wake aligned with the line-of-sight from the scanning lidar (wind direction shown by the blue arrow), while panel b shows the case of a wake not aligned with the line-of-sight from the lidar. The dashed arrow highlights the difference in the detected wake width for the two cases, at fixed downwind distance from the turbine (yellow ellipse)."

10. P12, Section 4.4: This comment relates to the Major Comments/Questions section above. Perhaps consider constructing a 3D volume of interpolated information, as opposed to compositing two horizontal planes for comparison. The change in wake centerline with height, supported by the presented measurements, is a really neat result of this study. The actual shape of the ellipsoid could potentially be better described (and compared to previous measurements) if the data were constructed in a 3D framework.

As already mentioned before, we thank the reviewer for their suggestion of a 3D volume of interpolated data; however, we decided not to implement this in our present work. At any rate, the results presented in Section 4.4 do NOT compare two horizontal planes, but two vertical regions, as shown in Figure 9 and in Figure 11, which we think is much more simple and intuitive than a real 3D framework to show our main finding of the vertical stretching of the structure of a wake, but with a lower magnitude than the ambient veer.

11. P12, L28: Why were the data separated between 55-75 m and >75 m, especially given hub height is at 80 m and data exist below 55 m within the rotor sweep. Why was the lower region bound vertically by 20 m but the upper region allowed to be larger? A quick comment on why this method was chosen could be beneficial.

The lower bin of data is between 35 and 55 m, and not between 55 and 75 as stated here. With this choice, we can have a great number of positions at low and high levels compared with the vertical dimensions of the turbines. By choosing these levels, we have an approximately equal number of vertical positions in each bin, given the geometry shown in Figure 2. To make this clear, we will include the following sentence: "these levels were chosen to create bins at low and high heights, compared to the vertical dimension of the turbines, with approximately the same number of vertical positions where the lidar measurements were taken, as shown in Figure 2".

MINOR EDITS:

1. P2, L16: "four" instead of 4.

2. P4, L15: The period at the start of this line should be at the end of the previous line.

3. P4, L23: "six" instead of 6.

4. P6, L14: Insert a period after (MAD).

5. P7, L11: Insert the word "the" between "as independent".

6. P9, L19: MAD is already defined on P6.

Thank you for catching all these edits! The manuscript will be changed accordingly.