Atmospheric
Measurement
Techniques

Discussions

Interactive comment on "Automated Wind Turbine Wake Characterization in Complex Terrain" *by* Rebecca J. Barthelmie and Sara C. Pryor

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This is a response to Reviewer 3: Interactive comment on "Automated Wind Turbine Wake Characterization in Complex Terrain" by Rebecca J. Barthelmie and Sara C. Pryor Atmos. Meas. Tech. Discuss., doi:10.5194/amt-2018-461-RC3, 2019

Our responses are given with ». A tracked changes version of the paper is attached. NB. The figures are shown at very low resolution to minimize the file size but they will be uploaded at high resolution for the paper.

Anonymous Referee #3 Received and published: 17 April 2019 Summary: The manuscript presents a method for detecting the location of the wake center from ground-based scanning Doppler lidar measurements, which is then applied to detect

the wake of a wind turbine on a crest. Results show that the detection of the wake works in the majority of the cases (against a subjective control). Further, the results show that, after an initial raise in the near wake region, the wake center descends following the terrain slope with a height a. g. l. depending on the stability parameter. Positive are the description of the challenges of scanning a wind turbine wake with a movable-head Doppler lidar and the interesting findings on the wake center evolution (especially considering the general sparsity in literature). Weak points are the description of the wake center detection itself and the presentation of some results could be improved (see main comments below). If those issues are addressed, the paper could be considered for publication. Main comments: 1) The description of method of the wake center detection should be improved (see detailed comments for pages 10 and 13 and Fig. 4). 2) The paper should touch upon possible false-positive detections of the wake center (see detailed comment on Fig. 12). 3) The presentation of some results could be improved and the observed dependencies could be quantified (see detailed comment on the lower panel of Fig. 16 and Fig. 17).

Language: I noticed a few missing comma and typos (see detailed comments for the ones I noticed). Given that I am not a native English speaker, there are probably more than those. Some phrasings are complicated and required me to read sentences twice to understand them. »We have clarified the text. Please see tracked changes version and the detailed explanation below.

Detail comments: Abstract, line 10: insert "a" in "by scanning" (the information that it is a ground-based scanning Doppler lidar and that Perdigão is in Portugal could be included, too). »Done. This now reads: 'An automated wind turbine wake characterization algorithm has been developed and applied to a dataset of over 19,000 scans measured by a ground-based scanning Doppler lidar at Perdigão, Portugal over the period January to June 2017.'

Abstract, line 11: "possible wake cases" could be more precise so that it relates to the wind speed and wind direction criteria. Added: "Potential wake cases are identified by

wind direction and the availability of retrieved wind speeds for both the freestream and the potential wake locations up to 4.5 rotor diameters from the wind turbine"

Abstract, line 12: The first association with "spit centers" is for me the (idealized) double-peak/donut structure of the wake near the nacelle. I believe the meaning here is more general and should be described more precise. »Changed to: 'The algorithm correctly identifies the wake centre position in 62% of possible wake cases, 46% having a clear and well-defined wake centre surrounded by a coherent area of lower wind speeds while 16% have split centres or multiple lobes where the lower wind speed volumes are no longer in coherent areas but present as two or more distinct areas or lobes.'

Abstract, line 16: In connection with the comments to Fig. 16 and 17, the word "strongly" could be replaced with a quantitative statement. »This has been modified to read: 'However, this behaviour is strongly linked to hour of the day and atmospheric stability. Overnight and in stable conditions, the average height of the wake centre is 10 m higher than in unstable conditions at 2 D downstream from the wind turbine and 17 m higher at 4.5 D downstream.'

Page 1, line 28: remove inner brackets at the citation »Done

Section 1.2: It would be a great improvement, if the flow behaviors introduced in this section would be picked up by the discussion of the wake center location in section 4.4. » We have modified Figure 14 to link back to the discussion of the inner-layer height and also introduced new text: 'Although the standard deviation of the wake centre height at each downstream distance is large, the tendency of the wake centre to initially loft and then move down the slope, broadly following the grade of the terrain, is clear. It is worth noting that the wake also expands as it moves downstream. Using equation (11), the wake width will be expanded from 82 m to 107 m after 2 D and to 137 m after 4.5 D (Figure 14). Although the tendency is for the whole wake to remain above the inner layer (discussed in Section 1.2), the lower edge of the wake is within 12 m of the

inner-layer height (and the uncertainty on both heights means it is plausible that the wake volume interacts with the inner layer, especially in unstable conditions. ' (Revised Figure 14 in attached file) Page 3, line 3: "in" instead of "is" »Done

Page 3, line 4: not sure, but I believe it is "interaction with" instead of "interaction of" »Done

Page 3, line 5 and line 9: L_h and H are introduced twice. »Changed (on what is now line 18)

Page 3, line 20: Based on Eq. (4), it seems that an overbar indicates averaging. Then the sensible heat flux in the text should also have an overbar. »Done

Page 4, line 12-13: The text in the brackets seems to be redundant to Eq. (8). » We've clarified this.

Page 5, Eq. (11): The variable x is sometimes an uppercase letter and sometimes a lowercase letter. Are they the same? If they are the same, then its usage should be consistent. » Lowercase x is used to indicate a location, like a co-ordinate whereas uppercase X is used to define a distance downstream of the wind turbine.

Page 5, line 14: It might be better to start with the dependency of k on various ambient parameters and then introduce the assumption of k=0.075 to get some approximate figures. »This value of k is recommended for use in the Jensen WAsP model for land sites. We've clarified that. 'where Dw is wake width in rotor diameters (D), D0 is the initial wake width, k is the rate of expansion (0.075 is recommended in WAsP for land sites (Katic et al., 1986), (Troen and Petersen, 1989)), which is determined by the factors listed above such as ambient turbulence intensity and X is the distance downstream.'

Page 9, line 39: Is this azimuth range (199-295_) the same for all elevation angles and other heights have more/less points (i.e. azimuth resolution changes) or is the azimuth range also different at other elevation angles? » This has been clarified –

also in Revised Figure 1 we now show the azimuth angles in a plan view inset figure. "Elevation angles are; 9, 10.5, 12, 13.5, 15, 16.5, 18, 19.5, 21 and 23ïĆř. The arc angle in the azimuth varies with the elevation angle. For 10.5ïĆř elevation and above, it comprises 23 beams from 199-259ïĆř with resolution between 1.5 and 6ïĆř (Figure 1). For 9ïĆř elevation, some of the outermost angles were removed because they returned very little data once vegetation had grown."

Page 10, line 20: I believe "wakes" should be singular. » Done

Page 10, lines 23-25: I did not understand this refinement of the first estimation. Why is it done for wind directions of exactly 210_ or 240_? As I understood it, this refinement works similar to first estimate, but with an extended vertical range and more elevation angles. Is that correct? (The sentence could be rephrased for better understanding). »p10, l31 We have rewritten this section to clarify the process: 'In the analyses presented herein the process for identifying potential wind turbine wakes cases that may have been sampled by the Galion lidar is multi-step. The VAD scans are used for the initial screening because they are much faster to process and determine whether there can potentially be a measured wake, depending on the wind speed and direction. First, the approximate wind speed and direction at a height above the Galion lidar equal to the WTHH ïĆś 30 m are estimated from the VAD scans as the maximum negative mean value of all valid radial velocities (where a signal to noise threshold (SNR) of 1.015 is applied) within each 10-minute period. If this analysis also indicated a wind direction of 210 or 240ïĆř (i.e. flow from the wind turbine toward the scanning lidar), the processing continues using the larger volume of the arc scans from the same 10-minute period. Arc scan radial velocities (SNR > 1.015) at a range of the distance to the WTHH+40 m and for scans at an elevation angle of 12-17ïĆř are used to refine the estimated inflow wind direction and wind speed. However, for some periods with low clouds/rain there are insufficient returned wind speeds at this distance ($\sim$1 km) to proceed.'

Fig. 4: A lot of the boxes have unclear labels and in some cases I cannot understand what the algorithm is doing exactly. I believe some of my problems come from incon-

sistent use of variables/names. Below are the problems I have: a) Differentiation of VAD DIR (wind direction retrieved from VAD scan?), PPI DIR (wind direction from the arc scans?), wake direction (the direction from the wind turbine to the Doppler lidar?), DIR (no idea), and wake DIR (short for wake direction?) »These are now defined on p6 and we use the same nomenclature throughout the paper and in this Figure: p6. 'Most frequently used scanning patterns comprise; one or more arc scans (in each arc scan the scan elevation angle is held constant while the azimuth angle is varied i.e. it is a pseudo Plan Position Indicator (PPI) scan in which the azimuth angle<360ïĆř) information, and/or Range Height Indicator (RHI) scans (varying elevation, fixed azimuth angle) and/or Vertical Azimuth Display (VAD) (high elevation angle, 360ïĆř scan at fixed azimuth angles).' Figure 4 caption: 'The following abbreviations are used DIR=direction, U=wind speed, VAD DIR=direction retrieved from VAD scans, arc scan DIR= direction retrieved from arc scans.' b) VAD DIR is used in the third check, but later it is checked, whether VAD values can be retrieved. »This has been changed to 'Retrievable VAD U' c) What is checked at the box with the label "Inflow U/DIR"? »We have changed this to' background U/DIR' and it is now consistent with the descriptive text on p12, l8: 'Then for each of the downstream distances considered (i.e. the vertical planes located at 2 D, 2.5 D, 3 D, 3.5 D, 4 D, 4.5 D) an assessment is made of whether there are sufficient retrieved radial wind speeds (i.e. measurements with a SNR > 1.015) to describe both the presence of a wake and the background flow field for each downstream distance and height.'

d) WTHHH should be WTHH? » This typo was corrected

e) Wake center location has arrows coming in from both "Vertical slice 2-6D" (I assume this would be the un-interpolated data) and "Cubic spline interpolation" (the interpolated data). According to the text, it is only detected from the interpolated data. If not, how are they combined? »This text has been clarified p12. l10: 'Once each case has passed these filters, radial wind fields on these planes are used to derive anomaly fields (see section 3.4) from which the wake centre location is identified and other wake

metrics are calculated for each downstream distance. The wake centre is calculated using both original data and cubic-spline interpolated fields.'

f) I assume that the box with "Gaussian fit" and "Wake metrics: : :" is part of the mentioned future work and not relevant for wake center location analyzed in this paper? Then they could greyed-out or removed. »The Gaussian fit was greyed out. As indicated, wake metrics include the wake centre location.

Page 13, line 7-8: The velocity deficit is introduced with two variables (delta U and v_d). »This has been corrected

Page 13, line 11: What does the "X D +/- 20 m" in the brackets mean? » This was changed in response to the comments of a previous reviewer.

Page 13, line 13-14: The sentence "Then the plane of radial velocities is discretized into 20 m horizontal planes and a mean radial velocity is computed." needs some clarifications: a) Are the radial velocities averaged or a corrected velocity depending on az/el of the beams and wind direction? b) If I understood correctly, the 20 m are referring to the vertical height of each plane – so that in the end a U_0 is gained that only depends on y and z? »Yes. That is correct. A background radial wind speed is determined for each distance downstream at discrete heights of 20 m. This has been clarified p14, l16 and we also refer to Figure 6. 'At each of these downstream distances ($\pm$ 20 m) the radial wind speeds at each x location (lateral displacement distance from a direct transect to the wind turbine) and z height (where z is defined from the elevation of the wind turbine hub-height) are retrieved for each 10-minute period. Then the vertical plane of radial velocities is discretized into 20 m horizontal planes and a mean radial velocity is computed for each 20m plane (see Figure 6).'

Page 13, line 15-16: The detection of the wake center should be explained in more detail. As I understood it, the algorithm searches the nearest local maximum from x=z=0.I did not understand what is meant with "refining that location by checking it moving around the grid cells". From the next paragraph, I understand that an inter-

polation takes place before detection of the wake center - that should be mentioned here. »This has been clarified p14, l19: 'Anomalies from that 'background' profile are then interpolated using cubic spline interpolation and used in the wake centreline identification. The location of the wake centre is determined using the maximum velocity deficit anomaly for each height starting its search at the expected location (WTHH). The location is refined by moving from that location horizontally replacing the wake centre if the new grid cell velocity deficit is greater than the previous maximum velocity deficit value. Once locations have been checked in each 20 m horizontal plane, the algorithm moves to the next vertical plane and checks that searching for the maximum velocity deficit value. The algorithm assumes the wake has moved further downstream than the immediate rotor plane after the double bell wake shape is expanded into a near Gaussian shape (Barthelmie et al., 2003) and hence that there is a well-defined centre. ' Fig. 5: It should be stated that axis are distance from the lidar. »This is in the caption to Figure 5. 'Each panel is 1000 m by 1000 m with the Galion located at (0,0) and depicts line of sight (radial) wind speeds from each elevation angle; 7, 9, 10.5, 12, 13.5, 15, 16.5, 18, 19.5, 21 and 23ïČř.'

Fig. 6 and Fig. 7: x and z could be used for axis labels. » The current version that states explicitly 'Height from WTHH' and 'Lateral distance' is clearer

Page 16, line 13: comma before but » A comma is not needed here. Commas are not required before the word 'but' unless two independent clauses are joined by the conjunction

Section 4.2 (headline): I believe "Data availability" would better describe the content of this section. Changed to '4.2 Data processing methodology and data availability'

Page 22, line 4: I do not understand what is meant with "wake centre of gravity". This was changed to p23, l3' B) type where the wake centre is split but the wake centre is broadly identified by the algorithm,'

Page 22, line 12: "at" instead of "as". » Done

Page 22, line 14: comma before but » Commas are not required before the word 'but' unless two independent clauses are joined by the conjunction

Page 22, line 14: I believe it should be either "identifies a part of the wake" or "identifies parts of the wake". » Done.

Page 26, line 11: Remove inner brackets and replace with "or" or "; also see" (I first thought it is a reference to section 1.2 in Whiteman and Doran). »Done

Fig. 12: The example of wake type B (and comparing it with with type D) makes me concerned about misdetections. How does the wake center of type B cases develop downwind – i.e does it evolve in a continuous manner or is the wake center "jumping arround" for successive downwind distances? For an automated wake detection, a quality flag system providing indication on the reliability of the detected wakes would be a great enhancement (beside the above, other possible routes could be the spatial standard deviation compared with the amplitude of the detected wake center or the number of local minima/maxima above a certain threshold). » There is a lot of work to do on these type B wakes. Thanks for the interesting suggestions. Given the length of the current manuscript we decided to focus on metrics of the A type cases here and follow with a detailed investigation of the much more complex B cases in a subsequent manuscript. For your interest, the lobes seem to be coherent as they move downstream but a much more comprehensive analysis is needed to confirm this and the other detail of their characteristics and behavior.

Fig. 16, lower panel: The usage of the symbols to show the hour of day is not working, because they cannot be read within the figure. And I could not make sense of the text in the top right (I got the z/L intervals, but what is the meaning of the S, N and U?). In my opinion, the time dependency is better illustrated in Fig. 15 and therefore Fig. 16 should focus on the dependency with the stability parameter. One idea could be, to pick one exemplary downwind distance and plot distance from WTHH vs. z/L. Then a linear fit /correlation (if significant) could quantify the relation with stability parameter. The

remaining downwind distances could be reported in the text or in a table. » The main point is to show both the general tendency that is really clear in the above figure and the variability by both hour and stability class. This helps to show that while the averages are really distinct there is still variability. It is not important to be able to distinguish the numbers on each line. We've added a detailed description of the two legends and also rewritten this section to illustrate the important points made by this Figure more clearly as below. The changes are clear in the tracked version of the paper provided: 'Thus, there is a tendency for the wake centre to be higher in stable than unstable conditions (Figure 16). The daytime hours of 09:00 to 17:00 UTC are largely associated with unstable conditions. During these hours of the day, the mean wake centre is slightly above the equivalent WTHH (+3.5 m) at a downstream distance of 2 D to an average of -50 m by a distance of 4.5 D (Figures 15 and 16). In stable conditions that prevail during 18:00 to 07:00 UTC, the mean wake centre is an average of +13.5 m from WTHH at 2 D and -33 m at 4.5 D. Most stable hours have wake centre trajectories that are higher than the majority of those in unstable hours (see the groupings of stable wake centre trajectories in blue colours vs the unstable wake centre trajectories in red colours in Figure 16). Despite this clear signal, there is also variability both in the grouping of individual hours into different stability classes and the height of the wake centre trajectory by stability. For the most extreme case of lofting, in the hour 21.00 (marked L) conditions are stable and the average of all values for the wake centre is +27 m at 2 D downstream but then descends to -38 m by 4.5 D. In contrast, at 8:00, an hour that is defined as near-neutral (marked 8), and at 13:00, an hour that is very unstable (marked D), the wake centre drops below -40 m after 3 D downstream. The behaviour of wakes is clearly very complex but despite a large amount of scatter, there is a consistent relationship between the value of z/L and the wake centre height for each downstream distance with wake centres in stable conditions being higher (Figures 15 and 16). ' Fig. 17: The color coding is unfortunate, because two similar greens and purples are used. Grey scales or a linear color map (e.g. blue -> red) would better illustrate a dependency. Similar to the comment on Fig. 16, the dependency could

be quantified with a linear fit and correlation (if significant). »The point is to show the general tendency of the relationship with wind speed. We evaluated various options and came up with the use of distinct symbols which, when combined with the colours, has improved this figure.

Section 5 (headline): "Summary" would be a better description for the content of the section. Changed to 'Summary and Conclusions'

Page 28, line 10: What is physical forcing? Physical forcing is generally understood to mean forces affecting on flow like the pressure gradient force, Coriolis force acting rather than thermally-generated mechanisms. To clarify this sentence we have changed it to 'There are very few near-neutral conditions and the lack of a clear diurnal signal in wind speed is indicative of multiple scale impacts on the flow, including both physical and thermal forcing. ' Page 28, line 18: Insert "to" between "applied identify" » Done

Please also note the supplement to this comment:
https://www.atmos-meas-tech-discuss.net/amt-2018-461/amt-2018-461-AC3-supplement.pdf