Reply to the comments provided by the Anonymous Referee #2 on the manuscript wes-2020-72 entitled "Optimal tuning of engineering wake models through LiDAR measurements", by L. Zhan, S. Letizia and G. V. Iungo

The authors are greatly thankful to the Reviewer for insightful comments. Our replies are reported in the following. References to pages and lines are based on the revised marked-up manuscript.

General comments

The research goals are relevant to field and motivated in the introduction. The methods are missing some essential information. Apart from the open questions arising from this missing information, the optimization and the results are presented in a clear and comprehensible way. The conclusions could be improved with recommendations for the application of the models. My main comments are (details in the specific comments below):… Overall, I recommend considering the manuscript for publication after the authors have addressed those points.

R: We thank the Reviewer for the positive feedback on our research strategy and the results achieved. We have added more comments and suggestions on the applications of the models following the Reviewer's comments.

1. *The manuscript is missing information on the Doppler LiDAR measurements and their processing.*

R: We agree that more details on the LiDAR measurements are needed for the sake of clarity, rather than only referring to Zhan *et al.* 2019. As reported at the Specific Comment 2, more information is now added to the text.

2. *The Jensen model and the Basthankhah model predict the normalized velocity deficit of the wake (Eq. 6 and Eq. 12). The optimization uses the longitudinal velocity (Eq. 1). Therefore, I believe an inflow velocity profile has to enter the optimization at one point, but the manuscript does not provide information on this.*

R: The Reviewer is right. This step of the post-processing of the LiDAR data was not described in detail and only referred to the previous paper Zhan *et al.* 2019. The calculation of the non-dimensional velocity field is now reported in the text (see Specific Comment 2).

3. *It is not clear which spatial volume is used to compute the error between the model and the LiDAR measurements and, therefore, it is difficult to assess if neighboring wind turbine wakes or offsets of the wake center position might affect the error unintentionally.*

R: The LiDAR scanning strategy was designed to only probe isolated wind turbines and to avoid wake interactions. At line 101, it is now reported: "According to the wind farm layout and the prevalence of southerly wind directions (Fig. 1), for wind directions within the sector 145° and 235°, the wakes produced by the turbines from 1 to 6 evolve roughly towards the LiDAR location, which is a favorable condition for the LiDAR to measure with close approximation the streamwise velocity through single-wake plan-position indicator (PPI) scans. Furthermore, according to the layout of Fig. 1(a), for the considered wind directions, these wind turbines are not affected by upstream wakes". Regarding the wake region considered for the optimal tuning of the model parameters, it is now reported at line 131: "… the mean percentage error (*PE*) calculated over the measurement domain with *x*-coordinates between 1.25 *D* and 7 *D*, while *r* between ±1.5 *D*".

4. *It might be interesting if the conclusions could elaborate on the following questions: What are the benefits of optimally calibrated models compared to using some of the general assumptions for the parameters found in literature? How transferable are the results of this optimization to other sites?*
R: For this project, we considered a typical utility-scale wind farm on flat terrain, with a typical daily cycle of the atmospheric stability for onshore sites. Therefore, we believe that the value obtained for the model parameters can be generalized to other onshore wind projects not affected by significant topography wind distortion. In the Conclusions at L 455, it is now reported: "The optimal tuning of the considered wake models has enabled to significantly reduce the mean percentage error in the predictions of the wake velocity field. For certain clusters of the LiDAR dataset, the mean percentage error has been four times smaller than for the respective baseline wake prediction obtained by using standard parameter values available from the literature. Considering that the wind farm under investigations is characterized by a typical layout, flat terrain and typical daily cycle of the atmospheric stability for onshore wind farms, we expect that similar improvements in wake-prediction accuracy can be generally achieved for wind farms with similar characteristics by using the reported optimally-tuned model parameters". Fig. 11 has been significantly revised by adding a direct comparison of the percentage error (PE) between the wake predictions obtained with the standard model parameters and the predictions obtained with the optimally-tuned models. The text at L 383-402 describes in detail the significant improvements achieved through the optimal calibration of the wake models.

Specific comments

1. *Figure 1: Panel (a) could use a scale and what is the time period used for the plot in panel (b)? Does it correspond to the data used in the results?*
R: A scale is now added to Fig. 1(a). In the caption of Fig. 1, it is now reported that the wind data used to calculate the wind rose were collected for the entire duration of the LiDAR experiment.

2. *Lines 93-99: Information is missing for the Doppler LiDAR: What was the elevation angle of the PPI scans? What was the azimuth step? How much time does each scan take? And how are the wake centered for the comparison with the model? A brief summary of the data processing would be helpful, even if it is described in detail by Zhan et al. (2019).*
R: At line 106, it is now reported: "The LiDAR measurements were typically performed by using a range gate of 50 m, elevation angle of ϕ=3°, azimuthal range of 20°, rotation speed of the scanning head of 2°/s, leading to a typical scanning time for a single PPI of 10 s. After rejecting LiDAR data with a carrier-to-noise ratio (CNR) lower than -25 dB, a proxy for the streamwise velocity is obtained through the streamwise equivalent velocity, $U_{eq} = V_r/[\cos\phi \cos(\theta - \theta_w)]$, where θ is the azimuthal angle of the LiDAR laser beam and θ_w is the wind direction. The streamwise equivalent velocity is then made non-dimensional through the velocity profile in the vertical direction of the incoming boundary layer. The latter is estimated for each PPI scan through the 70-th percentile of U_{eq} at each height. In Zhan *et al.* 2019, it was shown how this technique allows to remove turbulent gusts and LiDAR samples with reduced wind speed in correspondence of the wind-turbine wake. The reference frame used has x-direction aligned with the wake direction, which is estimated with linear fitting of the wake centers at various downstream locations. The transverse position of the wake center is defined as the location of the minimum

velocity obtained by fitting the velocity data at a specific downstream location through a Gaussian function".

3. *Eq. (1): Are the wake measurements of the LiDAR processed such that the wake is centered in the spanwise plane? Otherwise the error will include contributions from a different wake positions. And which downwind distances are used to compute the error?*
R: These details of the post-processing of the LiDAR data are now added to the text. At line 111, it is reported: "The reference frame used has *x*-direction aligned with the wake direction, which is estimated with linear fitting of the wake centers at various downstream locations. The transverse position of the wake center is defined as the location of the minimum velocity obtained by fitting the velocity data at a specific downstream location through a Gaussian function". At line 131: "… the mean percentage error (*PE*) calculated over the measurement domain with *x*-coordinates between 1.25 *D* and 7 *D*, while *r* between ±1.5 *D*".

4. *Eq. (1), Eq. (6), and Eq. (12): From Eq. (1) it seems that the model prediction of the mean longitudinal velocity field is compared with cluster-average from the Doppler LiDAR for the optimization. However, the Jensen model and the Bastankhah model predict the normalized velocity deficit in Eq. (12). To compute the longitudinal velocity field from the model, an inflow velocity profile is required. Therefore, the following things are unclear to me: where does inflow profile come from? Is it used to normalize the LiDAR measurements or combined with the model? Does it contribute to the model error?*
R: At line 110, it is now reported: "The streamwise equivalent velocity is then made non-dimensional through the velocity profile in the vertical direction of the incoming boundary layer. The latter is estimated for each PPI scan through the 70-th percentile of U_{eq} at each height. In Zhan *et al.* 2019, it was shown how this technique allows to remove turbulent gusts and LiDAR samples with reduced wind speed in correspondence of the wind-turbine wake".

5. *Figures 2a, 7a, and 7b: Some of the optimization clusters seem to hit a threshold (e.g. the optimization of the wake growth rate seems to plateau at 0.1 in Fig. 2a). Is there an explanation for this or could it be a too small search space of the optimization by mistake?*
R: We thank the Reviewer for this important comment. For Fig. 2(a), the wake expansion coefficient of the Jensen model, *k*, is varied between 0.001 and 0.3 (L 181). Therefore, the maximum value of about 0.1 is significantly below its upper limit. For Fig. 7(b), the maximum value of x_0 is 3.01, and indeed several cases hit the upper limit. However, this limit has been chosen based on the physical interpretation of x_0, which is the streamwise offset for the wake evolution, which should occur in the near wake. For the thrust coefficient of the Larsen model, which is reported in Fig. 7(a), an upper limit of 1 was set in the first version of the manuscript based on the model constraint connected with Eq. A3. However, considering that for the optimal tuning of the Larsen model, *Ct* is a free parameter, then the maximum value has been increased to 1.5. At L 287, it is now reported: "The thrust coefficient, C_t, is varied between 0.4 and 1.5 with a step of 0.01, c_1 optimal value is searched from 0.01 up to 0.25 with a resolution of 0.002, while x_0 ranges from 0.01 up to 3.01 with a step of 0.05. It is noteworthy that *Ct* values larger than 1 are allowed since the constraint of Eq. A3 is bypassed by considering *Ct* as a free input parameter". As shown in Fig. 7(a), several data clusters owing to region 2 of the power curve now achieve *Ct* larger than 1. Figs. 3, 6(a), 7, 10, and 11 have been updated accordingly.

6. *Line 308 and Figure 8: I have difficulties to relate the mentioned peak at 7% with the shown data. It seems that only two of the clusters have a peak and most not.*
R: This is now rephrased as (L 344): "A region with higher k_l is observed for *TI*<15%, then *kl* approaches zero for higher *TI* values".

7. *Figure 9: The caption should state that a normalized velocity is shown and that the green lines are the wake edge. Would it make sense to use σ as the wake width in case of the Basthankhah model?*
R: In Fig. 9(c), the wake edge is reported in correspondence of 2σ, which includes 95% of the total momentum deficit (Aitken et al. JTECH 2014). Caption of Fig. 9 is now: "Normalized velocity for the cluster with U_* of [0.76, 0.81] and *TI* of [13.5%, 19.4%] : (a) LiDAR data; (b) Jensen wake model; (c) Bastankhah wake model; (d) Larsen wake model; (d) Ainslie wake model. Green lines represent the wake edges, while for (c) they represent the spanwise position corresponding to 2σ".

8. *Figure 11: Which spatial volume is used for the computation of the percentage error? If large areas outside of the wake are used, then the error might also reflect undesired effects (e.g. neighbouring wind turbine wakes or inhomogeneous wind fields outside of the wake). Since the models only make predictions of the wake, it would be most sensible to use only the wake for the computation of the error.*
R: The Reviewer is right, the wake region where the *PE* is calculated is now specified in the manuscript. At L 131, it is now reported: "… the mean percentage error (*PE*) calculated over the measurement domain with *x*-coordinates between 1.25 *D* and 7 *D*, while *r* between ±1.5 *D*".

9. *Conclusions: I am wondering what is the gain in error reduction with optimally calibrated models compared to using frequently made assumptions in literature? For example how much lower is the error of the calibrated Jensen model or Basthankhah model compared to using wake growth rate assumptions provided by Fuertes et al. (2018) or Peña et al. (2015)? Alternatively, it might be interesting to investigate the error as a function of the model parameters to gain insights into the sensitivity of the error to the parameters.*
R: We thank the Reviewer for this important comment. We have now performed a direct comparison between the baseline wake predictions, which are obtained with the typical model parameters available from literature, and the respective ones obtained through the optimally-tuned parameters in terms of percentage error. This analysis is reported in the revised Fig. 11 and the text at L 382-404. We quantify the improvements in the model accuracy, which for certain clusters of the LiDAR dataset entails a reduction of the percentage error of about four times.

Technical comments

1. *Line 67: I believe the abbreviation SCADA was not introduced yet.*
R: It is now added.

2. *Line 88: The "while" in this sentence seems odd, because the topography data and meteorological data have no connection with each other.*
R: Revised.

3. *Line 89: Remove space before the comma.*
R: Revised.

4. *Line 95: Should be "of"instead of "on".*
R: Revised.

5. *Line 230: Remove the "e" before "Bastankhah wake model".*
R: Revised.

6. *Line 245: The citation should be "Larsen at al. (2003)" instead of (Larsen at al., 2003)".*
R: Revised.