Authors’ Response to Reviews of

Assessing the Accuracy of a Three-Year High-Resolution Mesoscale Wind Farm Wake Simulation with Lidar and Satellite Radar Data

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Wind Energy Science (WES) Journal,

RC: ***Reviewers’ Comment***, AR: Authors’ Response, ☐ Manuscript Text

List of relevant changes

- Appendix A2 has been added, included Figures A1, and A2 presenting a six-month sensitivity analysis of hub-height wind speed and wind directions using different α values in the Fitch scheme as requested by reviewer 1.
- The results in Sections 3.2.3 and 3.2.4 have been updated, as explained in the response to reviewer 2.
- Two additional Figures 16, and 17, have been included in the revised version, to support the requested momentum and thrust analysis.

1. Reviewer #2

1.1. General comments

RC: ***First of all, I commend the authors for conducting such a thorough revision of their work. I can see many changes in the revised manuscript in response to my comments and those of the other reviewers. I am mostly satisfied with their excellent responses, but have a few minor comments for consideration. The most important point: please consider the simultaneous roles of momentum extraction (and its dependence on wind speed) and wake recovery in the wake length discussions. The wake recovery is well described in the paper, but momentum extraction is a missing piece in describing the new Figure 15. Please adjust the Conclusions accordingly with any new insights.***

AR: Dear Reviewer,
We sincerely thank you for taking the time to review our manuscript. Your detailed and insightful comments have greatly helped us to better address the research gap and to further investigate the wake characteristics.

We would like to note a few updates on the revised version of the manuscript:

- The results in Sections 3.2.3 and 3.2.4 have been updated. In the previous version, the classification of wind direction (SW and NE) and wind speed regimes was based on the WF simulations, which represent an already waked inflow. In the revised analysis, the classification is consistently based on the NWF simulations, in line with the Obukhov length assessment within the same sections. This adjustment provides a more physically consistent framework for interpreting the results and strengthens the overall analysis. Consequently, minor updates are reflected in Figures 11-14 and Tables 4-5. These revisions lead to slight differences in the results but do not affect the conclusions.

- Furthermore, the wake area and wake length calculations have been refined (Table 6) by applying a more suitable map projection.
- We would like to note that the term "95% wake recovery region" has been changed to the more appropriate "5% wind speed deficit area", as we analyze both the blockage, intra-farm, and downstream regions, and not only the wake-recovery area.

Two additional figures have been included in the revised manuscript, along with further discussion in Section 3.2.4, aiming to analyze further momentum and thrust within the Belgian-Dutch cluster and the 5% wind speed deficit region:

- Figure 16 describes the momentum distributions within the blockage, farm, and downstream regions for each wind direction and wind speed regime.
- Figure 17 shows the streamwise wind speed deficit, thrust, and C_T within the Belgian-Dutch cluster.

Both Figures and the updated analysis are discussed in the comments below.

All changes and additions in the revised manuscript are highlighted in blue and enclosed in boxes.

1.2. Minor comments

RC: ***1. It would be good to specify what threshold you use to define the extent of the region affected by blockage (1%, 5%?). For instance, here: "For NE wind directions (Figure 13), the blockage effect is also visible, though it is confined to a smaller region, approximately 2 to 3 km upstream of the Borssele wind farm."***

AR: The whole analysis in Section 3.2.4 is conducted within the 5% wind speed deficit area. Even though this area is not depicted in the transects, i.e., Figures 12, and 13, we estimate the blockage area both from the transects and the wake maps in Figure 15. Lines 491-493 have been updated as follows

> A reduction in wind speed upstream of the wind farms is evident both under SW and NE wind directions. In the transect under SW winds (Figure 12), a noticeable wind speed deficit begins approximately 8 km upstream of the wind farm within the 5% wind speed deficit region.

RC: ***2. My understanding is that a more pronounced wake recovery leads to shorter wakes. Thus, it cannot be the reason for the longer wakes. Please consider the variability in thrust force with wind speed. Faster winds should produce stronger wakes (and wake recovery). This comment is based on the following statement: "When the flow transitions to higher wind speeds (above 5 m s-1), the wake structures become more coherent, with more pronounced wake recovery areas, leading to overall longer wake lengths (see Table 6)."***

AR: Thank you for this comment. Actually, it resulted from an imprecise phrasing in the paper, where by "pronounced wake recovery", we instead mean "larger areas with wind speed deficits", which understandably causes some confusion. As a result, we have corrected this phrase, focusing on the longer wake length and not the wake recovery area. Overall, the term wake recovery area has been changed to wind speed deficit area and updated in the revised manuscript. Lines 508-509:

When the flow transitions to higher wind speeds (above 5 ms[1]), the wake structures become more coherent, leading to overall longer wake lengths (see Table 6).

RC: ***3. Similar to the comment above, you included the following in the revised paper: "Greater wind speed magnitudes are associated with more pronounced downstream wind speed deficits (see Figures 12 and 13), as higher wind speeds in this region occur more frequently under neutral to stable conditions. Under these regimes, particularly during stable conditions, reduced turbulent mixing limits wake recovery, leading to enhanced and more persistent wakes [Rosencrans et al. [2024], Ali et al. [2023], Siedersleben et al. [2020]]. The transition toward neutral and stable ABL conditions with increasing wind speed may contribute to the higher cRMSE values observed in Tables 4 and 5, as these regimes are associated with enhanced shear." Here, it is important to separate the extraction of momentum within the wind farm and its recovery downstream. Examining Figure 15 is the key. You can see that for wind speeds greater than 5 m/s, the intra-farm area has a much darker shade of blue. This reveals that the cases with less than 5 m/s extract less momentum. Following the rule that the thrust force increases with wind speed squared, the cases with wind speeds greater than 5 m/s will extract more momentum and thus create a stronger deficit. Now, the part you well stated comes into play: depending on the atmospheric stability (which has a correlation with the wind speed classes) the wakes recover differently. Thus, I find it necessary to include the momentum extraction aspect in the discussion and clearly establish that the wake length depends both on the momentum extraction within the wind farm and wake recovery.***

AR: We thank the reviewer for this comment. It is indeed important to distinguish the pure wake recovery from the momentum extraction within the Belgian-Dutch cluster region. In Section 3.2.4, we have included Equation 5 that describes the average momentum per area and Figure 16 that presents the average momentum across the 5% wind speed deficit area, and the momentum extraction only over the Belgian-Dutch cluster, as well as the distributions of momentum (over the total 5% wind speed deficit area) in the blockage, farm, and downstream areas. It is indeed shown that with higher wind speed magnitudes, momentum extraction also increases. However, the overall 5% wind speed deficit area also increases, resulting in a higher redistribution of momentum downstream. Finally, we have included Figure 16 that illustrates the relationship between wind speed deficit, C_T, and thrust along the Belgian-Dutch cluster for SW and NE wind directions and across different wind speed regimes.

We have updated the methodology Section 2.1.1 as follows (Lines 140-146):

For simplicity, we consider the area-averaged momentum deficit:

$$\overline{\Delta M} = \frac{\sum_i^{N_c} \rho_0 \left(U_{\text{NWF}}^2 - U_{\text{WF}}^2\right) S_i}{\sum_i^{N_c} S_i}, \tag{1}$$

where ρ_0 is the density of the atmosphere near hub height, assumed constant and equal to 1.225 kg m^{-3}, S is the area of interest (e.g., the Belgian-Dutch cluster area), and N_c is the number of computational cells within this area.

The thrust force for each wind turbine is also computed, using the wind speed distribution provided by the Fitch scheme:

$$T = \frac{1}{2}\rho_0 C_T A_T U_{\text{WF}}^2, \tag{2}$$

where A_T is the area swept by the rotor blades, estimated using the rotor diameter of each turbine.

Results Section 3.2.4 has been updated as follows, and lines 512-545 have been added:

Figure 16 summarizes momentum characteristics within the 5% wind speed deficit area. We apply Equation (1) using hub height wind speeds, with $\overline{\Delta M_T}$ evaluated over the total 5% wind speed deficit area, and $\overline{\Delta M_F}$ over the Belgian-Dutch cluster area only to isolate the momentum extraction due to the wind turbines. Both $\overline{\Delta M_T}$ and $\overline{\Delta M_F}$ increase with wind speed (Figure 16 A), due to enhanced turbine-induced momentum extraction at higher wind speeds. Under NE wind direction, where the flow interacts first with the coarser Borssele zone, the overall momentum distributions ($\overline{\Delta M_T}$ and $\overline{\Delta M_F}$) display a more consistent, near-linear increasing trend over the wind speed range of 5 to 15 m s^{-1}. The fractions of blockage, farm (i.e., the actual momentum source), and downstream momentum distributions over the total 5% wind speed deficit area are presented in Figure 16 B (SW) and C (NE). An increase in momentum redistribution within the blockage zone is observed for wind speeds between 5 and 8 m s^{-1}. Furthermore, although higher wind speeds enhance momentum extraction from the wind farms, the concurrent expansion of the 5% wind speed deficit area results in greater downstream momentum redistribution.

Figure 17 presents the streamwise normalized wind speed deficit ΔU_{wake}, thrust, and turbine C_T within the Belgian-Dutch cluster. All streamwise quantities are averaged over the spanwise direction, considering only grid points corresponding to wind turbine locations (i.e., excluding surrounding flow regions without turbines). The thrust coefficient C_T is computed utilizing the C_T curves provided in the wind turbine files used for the Fitch simulations (see Table A1). Consistent with the preceding analysis, all quantities are estimated using wind speeds at a uniform hub height of 107 m. The streamwise-averaged wind turbine density is shown in the light-blue bins, with higher density indicating the Belgian offshore zone. Under SW wind directions and low wind speed regimes (Figure 17 A1), an increase in ΔU_{wake} is observed, accompanied by a decrease in thrust as the flow crosses the dense Belgian offshore zone. The wind speed deficit then decreases within the coarser Borssele zone, consistent with the prevailing very unstable stability conditions presented in Figure 14 A. Although the trends in the streamwise wind speed deficit and thrust curves are similar at higher wind speed regimes, for wind speeds between 11 and 15 m s^{-1} (Figure 17 D1), ΔU_{wake} shows a slight increase within the Borssele zone that can be associated with the transition to neutral and stable conditions (see Figure 14 A).

Under NE wind speeds, the streamwise trends differ, as the flow first encounters the coarser Borssele zone. Similarly to SW regimes, for wind speeds below 5 m s^{-1}, the wind speed deficit remains relatively low, likely associated with the prevailing very unstable conditions that favor faster wake recovery, even within the Borssele zone. In the 5-8 m s^{-1} wind speed regime, there is a more gradual increase in the wind speed deficit, resulting in a decrease in thrust that begins to stabilize within the Belgian offshore zone. The trends at wind speeds between 8 to 11 m s^{-1} and 11 to 15 m s^{-1} are consistent, with a modest increase in thrust at higher wind speeds.

Overall, across all cases, higher wind speeds are associated with increased ΔU_{wake} and thrust, followed by a transition to neutral and stable conditions. The thrust coefficient C_T remains generally constant, showing minor increases in denser turbine regions. For NE wind direction at high wind speeds, C_T is lower in the front rows of the Borssele wind turbines, likely due to the higher inflow velocities. Furthermore, the slight increase in ΔU_{wake} observed in the front rows may reflect the development of the turbine induction zone. The complex layout of the Belgian-Dutch cluster layout results in notable differences between SW and NE wind directions and varying wind speed conditions.

Conclusions have been updated as well (lines 664-668):

Momentum extraction, expressed as momentum deficit within the Belgian-Dutch cluster, increases with wind speed due to the higher incoming momentum. At higher wind speed regimes, thrust increases, with localized reductions occurring in dense wind turbine regions, reflecting the corresponding decrease in wind speed. In addition, at lower wind speed regimes, an upstream wind speed reduction zone is observed, consistent with enhanced upstream redistribution of momentum.

References

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