

Paper Review - WES-2026-140

Title: Mitigating wind farm cluster wakes by vertical staggering

October 4, 2026

The authors use large-eddy simulations (LESs) to investigate the effects of vertical turbine staggering on the flow surrounding an isolated wind farm (WF1) and two aligned wind farms (WF1 and WF2). Each of these conditions is studied both with and without vertical staggering on WF1, and under different staggering layouts. In my opinion, the results presented in the manuscript cannot be considered as a major research breakthrough on the wake dynamics of large clusters but rather as a valuable building block in this direction. Specifically, two aspects of this study are in my opinion clearly novel, namely

- The authors use a conventionally neutral boundary layer (CNBL) as a freestream/background condition for their analysis. This increases the level of realism of their simulations, uncovering physical processes that are either not present or drastically less pronounced under truly neutral conditions. While other studies exist that used a similar setup, the majority of wind farm wake studies focused on truly neutral conditions.
- The authors both looked at the wake of the upstream and the downstream clusters. Combined with the previous point, this makes the present study extremely valuable and insightful in understanding the dynamics of large cluster wakes.

There are also additional interesting findings that are well related to previous literature, both when they agree or disagree with it. Examples of this are the acceleration region on the North side of the wake, the minor role that vertical turbulent transport has in the far wake, the potential presence of Prandtl's secondary flow, and the non univocal positive effect of vertical staggering on wind farm wake recovery.

Furthermore, I would like to note that the manuscript is extremely well written and organized, and the analysis presented by the authors is in my opinion rigorous, honest and detailed. The many important links to previous literature allow the reader to really appreciate how the manuscript builds on previous research and, where applicable, extends the state of the art. I appreciate the care that has been taken in preparing and reviewing the manuscript before submitting it for review.

For all the reasons above, I strongly support the manuscript publication in the Wind Energy Science Journal with only some minor adjustments and suggestions that are outlined in Sec. 1.

1 Specific Comments

line 17: the authors mention in the abstract that vertical staggering results in a "a better wake recovery at lower hub heights inside the wind farm". I would either remove or change this sentence because it is misleading and reductive in my opinion. To my understanding, this is not quite what's happening. The staggered wind farm simply has less

thrust applied at the lower hub height, so it would be more correct (and this is shown by the wind speed evolution at the lower hub height) to say that wake deficit is distributed over a taller layer of the ABL. Consequently, it is straightforward to me that deficit is reduced when only looking at the hub-height. However, additional physical processes take place inside the wind farm, the most important being the streamwise streaks and the turbulent advection of low wind speed from above (for the staggered cases), which hinders wake recovery especially in the wind farm near wake. For these reasons I would leave the above mentioned sentence out. The taller turbines and a lower rotor density per height are in my opinion sufficient to explain the increase in WF1's power.

lines 40-45: to better explain the role of the Coriolis force I would suggest the authors to add the citations of van der Laan and Sørensen (2017) and Bastankhah et al. (2024). These studies show interesting insights on how the Coriolis force deflects the flow inside and in the wake of the wind farm, i.e. through counteracting direct and indirect effects. Mentioning these effects is important, given the nature of the manuscript, and would in my opinion improve the completeness of the introduction section.

line 56: I would remove the word "realistic", as the kind of CNBL that is simulated in LES is still an idealization w.r.t. what happens in real life. Alternatively, I would suggest the authors to change it to something similar to "CNBLs increase the realism of the simulations compared to truly NBL".

line 155: Please change "Earth's angular velocity Ω " to "Earth's angular velocity magnitude Ω ".

line 177: please include the value of the Rayleigh damping coefficient and how it was calculated (e.g. using the methodology proposed by Lanzilao and Meyers, 2022).

section 2.1 in general: it seems that the simulations conducted by the authors are quite large. From my calculation the number of cells exceeds 10 billion. If this is the case, these are among the largest wind farm simulations ever conducted. For this reason, I would appreciate more info on e.g. the number of cores used and an idea on the computational time required for both the precursor and the successor. It is important in my opinion to keep track of these parameters as well.

line 230: e_{SGS} cannot be calculated from the LES fields unless a prognostic equation is solved for it. Is that what the authors are doing in the PALM model?

lines 455-456: I disagree that "the deficit of B1 is mostly constant". I would say that, in the second wind farm, the deficit of B1 goes like S1, with the latter just exhibiting slightly higher deficit.

Figure 9 caption (and in other places, where applicable): please change "dotted" with "dashed".

lines 471-472: "compared to the deficit behind...", this makes things confusing. What the authors are showing in Fig. 9a and 9b is not deficit, but rather wind speed. When the authors say that the deficit behind the second wind farm (70%-75%) is stronger than the first wind farm (80%-90%), they should either show the complementary percentages, i.e. 30%-25% vs 20%-10%, or directly refer to the wind speed.

Figure 13(a and d): this is just a suggestion, but I believe that the legends should be S1-B1/S3-B1 and S1-B2/S3-B2, respectively (following the rest of Figure 13), as it took me some time to understand what I was looking at.

lines 524-526: the sentence "Both vertical staggering setups show throughout the wind farm an increasing power production relative to B2, where the second half of the wind farm has on average a larger power production than B2" is not very clear to me.

line 644: it is not clear if the authors did or did not repeat these simulations. Please clarify.

Section 4.3: this is just a suggestion, but I struggled a bit to relate North with left and South with right at the beginning. Please consider making this more explicit for better readability.

line 767: could the stronger speedup in the staggered cases be explained simply because the effective height of the wind farm w.r.t the ABL is higher in these cases? Adding this also here would make things clearer in my opinion.

Appendix A2: please consider adding (a small) explanatory text to this section. I am personally against sections containing only figures.

References

- Bastankhah, M., Mohammadi, M. M., Lees, C., Diaz, G. P. N., Buxton, O. R., and Ivanell, S.: A fast-running physics-based wake model for a semi-infinite wind farm, *Journal of Fluid Mechanics*, 985, A43, <https://doi.org/10.1017/jfm.2024.282>, 2024.
- Lanzilao, L. and Meyers, J.: An Improved Fringe-Region Technique for the Representation of Gravity Waves in Large Eddy Simulation with Application to Wind Farms, *Boundary-Layer Meteorology*, <https://doi.org/10.1007/s10546-022-00772-z>, 2022.
- van der Laan, M. P. and Sørensen, N. N.: Why the Coriolis force turns a wind farm

wake clockwise in the Northern Hemisphere, *Wind Energy Science*, 2, 285–294, <https://doi.org/10.5194/wes-2-285-2017>, 2017.