

Response to Reviewers' Comments:
*Differences in cluster and internal wake effects from
mesoscale and large-eddy simulations off the U.S. East Coast*

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Reviewer comments are shown in roman typeface, authors' responses are shown in [blue](#), and modifications to the text are shown in *blue italics*. Figures referenced in the response to reviewers' comments but not included in the revised manuscript follow the naming convention "FIGURE R#", otherwise figures referenced in the response to reviewers' comments correspond to the revised manuscript.

Major changes made to the manuscript include:

- New figure showing mesoscale and LES domain configuration.
- Modifications in the text to improve readability.
- Clarifications on the impact of turbine position errors.
- Updated affiliation of several coauthors.

Reviewer 1

The work addresses a highly relevant issue and provides a thorough comparison of the two methodologies. It is of high scientific quality and well formulated. I believe it is ready for publishing given a few minor revisions and technical corrections.

The authors appreciate the reviewer's comments. We clarified the limitations of our comparison and modified the figures accordingly to improve readability.

Major comments

The manuscript quantifies the difference in turbine position between mesoscale and LES in section 2.1 but then there is very little discussion on the effect of that change in positions, especially on the internal wakes. If that is not possible the change in positions should be quantified in some other way.

Thank you for this comment. The authors agree that one source of uncertainty in the internal wake effect estimates is the difference in turbine positions between the LES and mesoscale and the resulting alignment offset. Directly quantifying the effect from the discretization error would require running LES using the turbine positions of the mesoscale simulation. However, this is unfeasible given that this project has now concluded. Instead, we highlight this source of uncertainty in the manuscript and indicate its potential for future work.

We expanded Section 2.1 to include the mean and maximum difference between the simulated turbine positions in the mesoscale and their physical location:

Lines 160–163: *Due to the domain discretization and because the turbines are represented at the grid cell center, the simulated turbine positions in the mesoscale simulation differ from their physical location (Fig. 2). On average, the simulated turbine positions in the mesoscale are displaced by 400 m ($\sim 2D$) from their physical position, with a maximum displacement of 700 m ($\sim 3.4D$).*

We also address this uncertainty in Section 5.2, as follows:

Lines 368–371: *Internal wake effects are generally not well captured by the mesoscale simulations for the wind direction sectors considered here (Fig. 15). In general, the agreement between the LES and mesoscale simulations increases as the effective turbine spacing d_{intra} becomes larger. As the effective turbine spacing increases, the impact of the mesoscale discretization (i.e., error in turbine position and alignment offset) likely diminishes due to the wake expansion.*

Finally, we highlight this limitation that is inherent to mesoscale simulations in the conclusions and suggest future work, as follows:

Lines 456–458: *In addition, the discretization of turbine positions in the mesoscale grid introduces offsets from their physical locations that modify the effective directions of alignment and turbine spacing, contributing additional uncertainty to internal wake estimates.*

Lines 476–478: *Future work should directly quantify the contribution of turbine position errors in the mesoscale grid to the uncertainty in internal wake estimates, for example, by comparing simulations with physical and discretized turbine positions under otherwise identical conditions.*

Minor comments

1. Please clarify l. 356ff.

We clarified this sentence as follows:

Lines 362–366: *Interestingly, the average normalized power remains similar between the LES and mesoscale simulations ($\hat{P} = 0.91$ and $\hat{P} = 0.92$, respectively). This agreement arises because, in the mesoscale simulations, front-row turbines at Sunrise Wind wake their neighbors for wind directions between $230^\circ \leq \phi < 240^\circ$. As a result, both the numerator and denominator in Eq. (5) are reduced, such that the relative power difference between freestream and cluster-waked turbines remains comparable across both approaches.*

2. l. 277: “..also cannot also ...”

The text was updated accordingly.

3. The dotted black lines in figures 5, 6,7,8,9,11,12 and 14 are very hard to differentiate from solid lines, please consider a wider spacing of the dots.

Thank you for your suggestion, we updated Figure 12,13, and 14 accordingly to differentiate the solid and dashed lines. We also modified Figures 6–10 to make the transects more visible. Figures 6 and 13 below illustrate the changes:

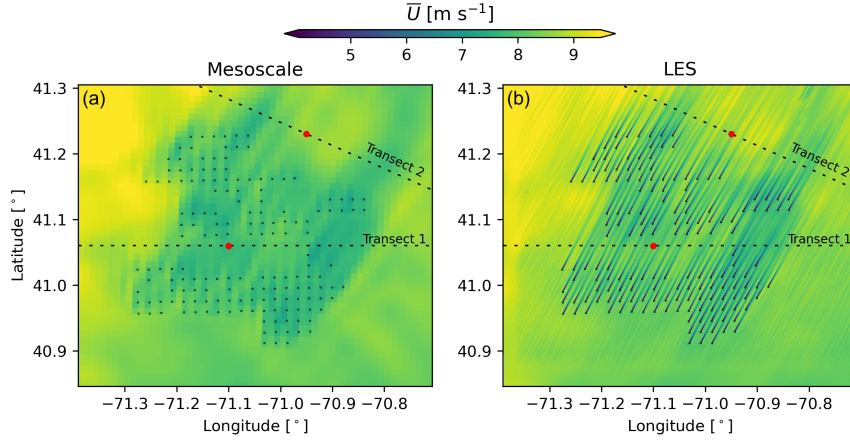


Figure 6. Time-averaged velocity field at hub height for the mesoscale (a) and LES (b) simulations on 4 November 2020 at 20:37 UTC. The dotted black lines in each panel illustrate the locations of the velocity transects, and the red dots indicate the midpoint distance of each transect.

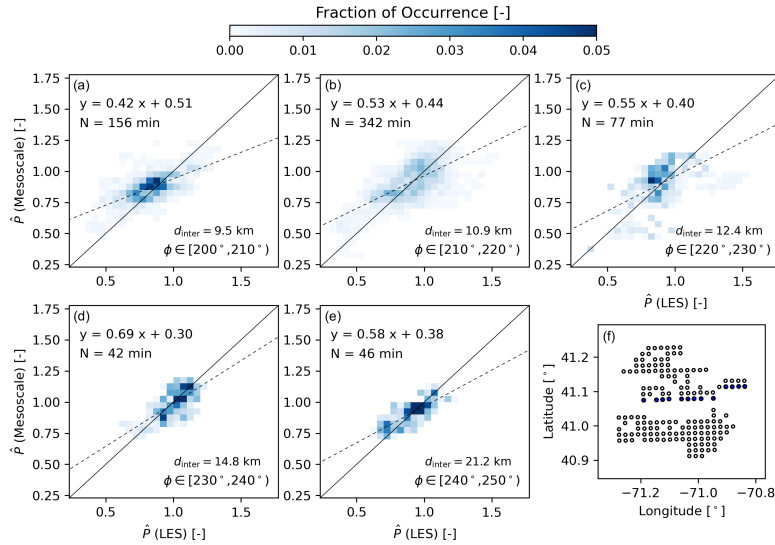


Figure 13. Normalized power production for turbines experiencing cluster wakes for wind direction sectors $200^\circ \leq \phi < 210^\circ$ (a), $210^\circ \leq \phi < 220^\circ$ (b), $220^\circ \leq \phi < 230^\circ$ (c), $230^\circ \leq \phi < 240^\circ$ (d), and $240^\circ \leq \phi < 250^\circ$ (e). The turbines considered here are represented by blue circles in Panel (f). The black solid line in panels (a–e) represents the 1:1 correspondence between the data, and the black dashed line corresponds to the linear regression to the data, given in the top-left corner of each panel. The effective distance between the last-row turbines in Sunrise Wind and the southernmost turbines in South Fork and Revolution Wind (d_{inter}) is also shown in each panel.

Reviewer 2

The authors evaluate the capabilities of mesoscale simulations in predicting the wake effects on wind turbine power production. A comparison between mesoscale Weather Research and Forecasting simulations and large-eddy simulations for three planned wind farms under realistic atmospheric conditions is made. The WRF simulation is found to be capable of capturing the velocity deficit downstream of both single and multiple wind farms. However, the simulations under-estimate the power loss due to internal wakes, but provide accurate estimates of the combined wake losses from internal and cluster wake effects across some wind direction sectors. The findings suggest that mesoscale simulations are a viable tool for predicting wake effects for wind farms. The manuscript is generally well written and the results are of interest to the wind energy community. I recommend its publication with the following comments:

We appreciate the reviewer's suggestions. We addressed the reviewer's comments by clarifying how velocity variances are treated in the mesoscale simulation and including an additional figure in the text.

Major comments

1. Although the wake effects are weaker under unstable conditions, the influences of the horizontal wind fluctuation variances may be stronger. How well does the WRF model parameterize them?

Indeed, horizontal velocity variances influence mixing and, consequently, wake evolution under unstable conditions.

Mesoscale simulations do not explicitly include the effects of horizontal velocity variances in the momentum equations, whereas LES does. The MYNN boundary-layer parameterization includes only contributions from the vertical fluxes of horizontal momentum (i.e., $\langle u'w' \rangle$ and $\langle v'w' \rangle$) in the momentum tendency equations via a gradient-diffusion approach, expressed as $\langle u'_i w' \rangle \sim \hat{k} L S_i \partial U_i / \partial z$, where \hat{k} is the estimated turbulent kinetic energy (TKE), L is a mixing length scale that varies with atmospheric stability, S_i is a stability function, and $\partial U_i / \partial z$ is the vertical gradient of the mean wind component (Nakanishi and Niino, 2009). The effects of horizontal velocity variances are instead represented through the TKE tendency equation. Therefore, enhanced mixing under unstable conditions associated with horizontal velocity variances is manifested through modifications to the stability functions, increased TKE, and larger mixing length scales.

In the LES, the effect of the increased horizontal velocity variances are accounted for in two ways: from resolved eddies and the subgrid-scale turbulence closure. The NBA turbulence closure employed here models subgrid-scale turbulence mixing using the subgrid-scale TKE (e), the local strain rate tensors (S_{ij}), and a length scale (l). Chen and Tong (2006) demonstrated improved performance in representing subgrid-scale turbulence stresses with the NBA closure; therefore, the LES provides a more faithful representation of the effects of horizontal velocity variances on wake evolution under unstable conditions than the mesoscale simulations.

We include the following in the text to clarify this point:

Lines 264–270: *Under unstable stability conditions, individual turbine wakes generally merge with the larger-scale cluster wake before reaching downstream clusters (Fig. 7). As a result, the difference between the wake in the LES and mesoscale simulations is smaller. This faster wake recovery under unstable conditions is driven by enhanced turbulent mixing associated with larger turbulent stresses. In the mesoscale simulations, these effects are represented implicitly through increases in TKE and stability-dependent mixing length scales within the boundary-layer parameterization (Nakanishi and Niino, 2009). Conversely, the LES explicitly resolves the dominant turbulent eddies responsible for enhanced mixing, providing a more direct representation of these effects.*

2. In figure 1, what is the relative location of panels (a) and (c) in the mesoscale simulation? Are panels (b) and (d) the full LES domain?

Thank you for raising this concern. We did not have a figure showing the location of the mesoscale domains, and their size relative to the LES. We added a new figure to the manuscript showing the domain configuration and the relative size of the LES domain compared to the mesoscale.

Lines 116–117: *A three-domain, one-way nested setup is used to evaluate cluster and internal wake effects in the mesoscale simulation framework (Table 1), following Xia et al. (2025). The size and position of the mesoscale domains is shown in Figure 1a.*

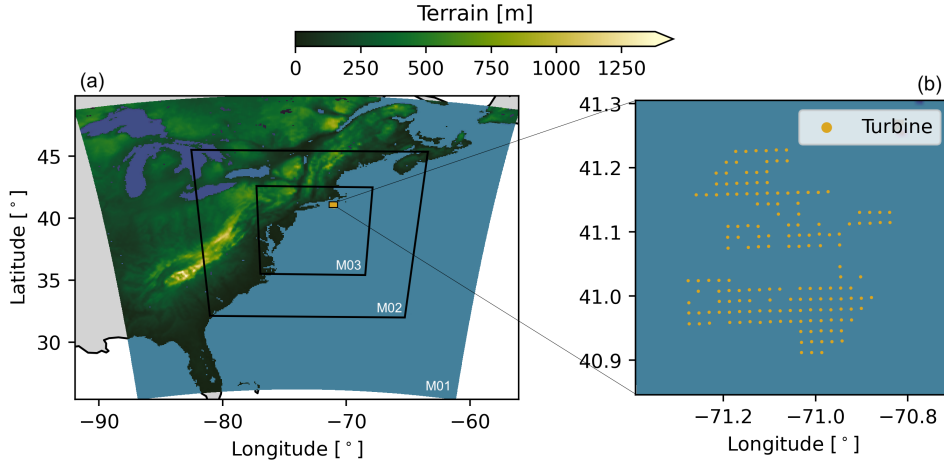


Figure 1. Domain layout for the mesoscale (a) and LES (b) domains. The location of the turbines within the LES domain is also shown.

3. The linear regression in Fig. 11 appears to underestimate the slope of the fit (and hence perhaps the performance of the WRF model), likely due to the relatively small number of data points. Kernel methods (Kernel Smoothing, M.P. Wand 1994) in general can greatly improve the regression accuracy. I suggest that the authors give it a try.

We appreciate the reviewer’s suggestion to use kernel methods instead of the linear fit. We repeated the analysis using kernel methods to find the relationship between the LES and mesoscale data (Figures R1 and R2).

Overall, we find that a linear regression provides an adequate representation of this relationship across the range of well-sampled conditions. In regions with sufficient data density, the slope of the linear regression (thin dashed line) closely matches that of the weighted local linear regression (thick dashed line), as shown in Figure R1. Differences between the two approaches emerge primarily in sparsely populated regions (e.g., where $\hat{P}(\text{LES}) < 0.5$). In these cases, the divergence reflects the limited data available rather than a systematic shortcoming of the linear model. We therefore consider that the data in these regions are insufficient to support a reliable inference of the underlying relationship. We performed an analogous analysis for the yaw-binned normalized power in the cluster-waked case and observed similar behavior (Figure R2).

Based on these results, we conclude that the linear regression captures the dominant trend in the data while remaining straightforward to interpret. For this reason, we have retained the linear fit in the manuscript.

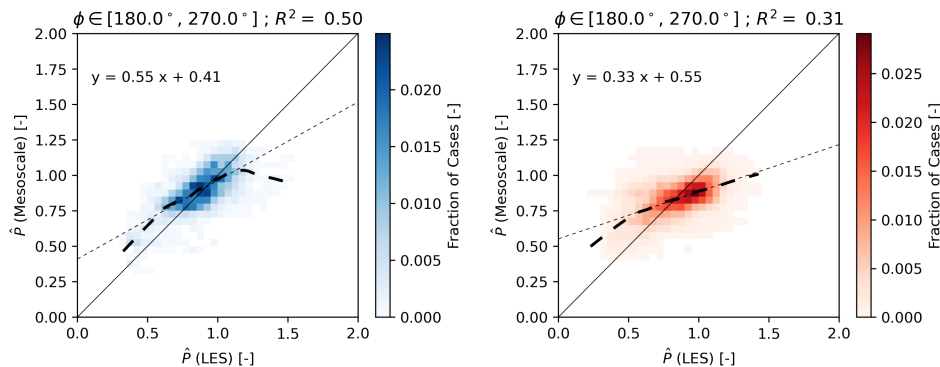


Figure R1. Normalized power production for turbines experiencing cluster wakes (a) and internal wakes (b) across all the wind direction sectors. The black solid line in each panel represents the 1:1 correspondence between the data. The thin black dashed line corresponds to the linear regression to the data, given in the top-left corner of each panel. The thick dashed line corresponds to the fit using a weighted local linear regression.

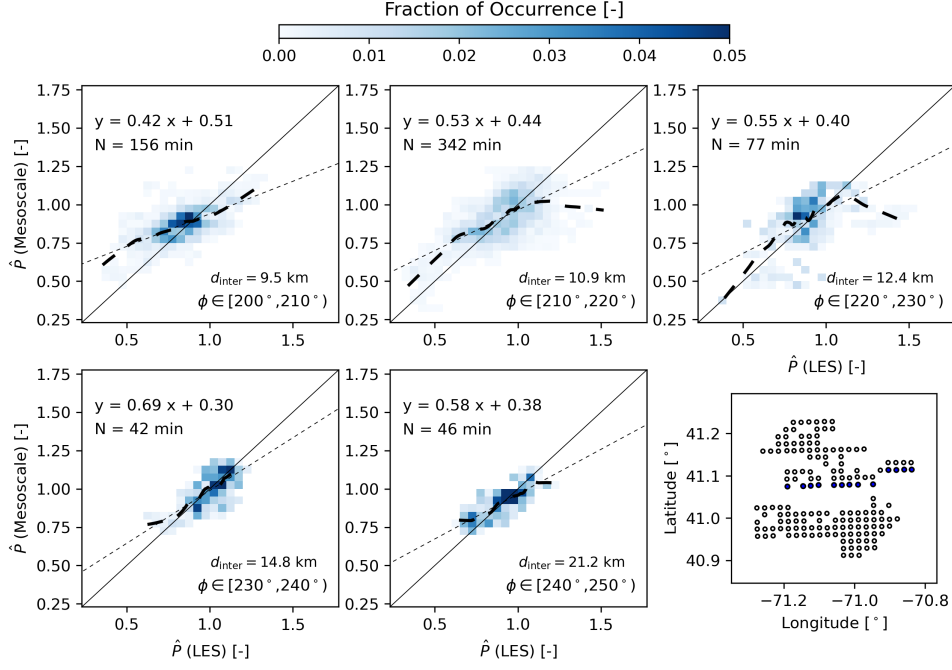


Figure R2. Normalized power production for turbines experiencing cluster wakes for wind direction sectors $200^\circ \leq \phi < 210^\circ$ (a), $210^\circ \leq \phi < 220^\circ$ (b), $220^\circ \leq \phi < 230^\circ$ (c), $230^\circ \leq \phi < 240^\circ$ (d), and $240^\circ \leq \phi < 250^\circ$ (e). The turbines considered here are represented by blue circles in Panel (f). The black solid line in panels (a–e) represents the 1:1 correspondence between the data, the thin black dashed line corresponds to the linear regression to the data (given in the top-left corner of each panel), and the thick dashed line corresponds to the fit using a weighted local linear regression. The effective distance between the last-row turbines in Sunrise Wind and the southernmost turbines in South Fork and Revolution Wind (d_{inter}) is also shown in each panel.

References

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- M. Nakanishi and H. Niino. Development of an Improved Turbulence Closure Model for the Atmospheric Boundary Layer. *Journal of the Meteorological Society of Japan*, 87(5):895–912, Jan. 2009. doi: 10.2151/jmsj.87.895.
- G. Xia, M. Optis, G. Deskos, D. M. Hernando, J. K. Lundquist, M. S. Gomez, A. Kulmer, M. Sinner, P. Fleming, and W. Musial. Understanding Cluster Wake-Induced Energy Losses Off the U.S. East Coast, 2025. URL <https://www.ssrn.com/abstract=5248813>.