Response to reviewers' comments

for the paper: "Slow wake recovery and low turbulence behind wind farms parameterized in mesoscale simulations"

under review in *Wind Energy Science.*

Regular font – reviewers
Bold blue font – authors

Response letter to Referee #1

Referee comment: The manuscript has been improved, particularly in its choice of wording. Replacing the term "under-resolving gradients'' is a positive step, as the previous formulation was misleading, as noted by the other reviewer. I also welcome the revised phrasing in the title and discussion, which now presents a more neutral tone and avoids overstating the findings. However, the newly introduced term "underestimated'' is still not appropriate for this context. Since the revision primarily involves changes in wording, my comments focus on this aspect. I have only a few remarks which once addressed, I would be satisfied for publication. I commend the authors for all their efforts so far, and I believe the manuscript is close to being publishable. All line numbers below refer to the revised version.

Response: We thank the referee for carefully reading the revised manuscript and for the constructive comments. Below, we respond point by point and describe the corresponding revisions.

Major comment

Referee comment: The authors have replaced "under-resolved'' with "underestimated.'' Although this is an improvement, the new term remains misleading. Coarse mesoscale simulations inherently represent gradients at their own resolution, while finer-scale gradients,

as captured by LES, are simply not resolved by the coarse simulations. Consequently, such gradients will always appear underestimated or under-represented when compared to higher resolution results. This is an expected consequence of coarse gridding.

The authors state that the coarsened LES is used only as a diagnostic and does not represent the true dynamics governing wake recovery. While I agree, the ultimate goal is for the NWP-WFP simulations to reproduce the behaviour of the coarsened LES by parameterising the underlying dynamics observed in high resolution simulations. In its current form, the NWP-WFP framework does not adequately capture these effects.

For these reasons, the term “underestimated’’ should be avoided except when explicitly comparing NWP-WFP simulations with coarsened LES. For example, Section 3.5 could be retitled “Coarse resolution effects in the wake of …”, and Section 4.1.1 could refer more generally to “Coarse grid effects.’’ These are only suggestions and the authors may propose better alternatives, but the key point is to avoid potentially misleading terminology.

Finally, Fig. 10 should include the coarsened LES results to show the comparison with NWP-WFP simulations and to illustrate how spatial averaging smooths local gradients.

Response: The term "underestimated" has been revised throughout the manuscript to avoid implying a model error in the conventional sense. Coarse mesoscale simulations inherently represent gradients at their resolution, and the lower spatial gradients they resolve compared to LES are an expected consequence of the coarser grid rather than a model error in the wind-farm parameterization itself. Nevertheless, the grid-resolution-imposed limitation directly affects shear production and wake recovery in NWP models, which are the central focus of our analysis. The manuscript makes this distinction explicit throughout. To reflect this, we refer to "coarse-grid effects" or "weaker spatial gradients" depending on the context and retain "underestimated" only when an explicit quantitative comparison with the coarsened LES is made. Following the referee’s suggestions, we have revised the relevant section titles:

“Section 3.5 Coarse-grid effects on wind-farm wake spatial gradients”

“Section 4.1.1 Coarse-grid resolution weakens spatial wind speed gradients”

We discuss results for the coarse LES in the revised Fig. 10 (below) in the revised text as follows. In lines 426–427:

“Mesoscale simulations consistently reproduce the streamwise evolution of the wind speed and TKE profiles relative to the coarse LES for the aligned layout. The TKE100 case agrees more closely with the coarse LES than the BASE case, particularly for TKE. Nonetheless, negative biases in wind speed and TKE increase downstream.”

Also in lines 458–460:

“Similar to the mesoscale simulations, the coarse LES exhibits weaker vertical gradients owing to horizontal averaging.”

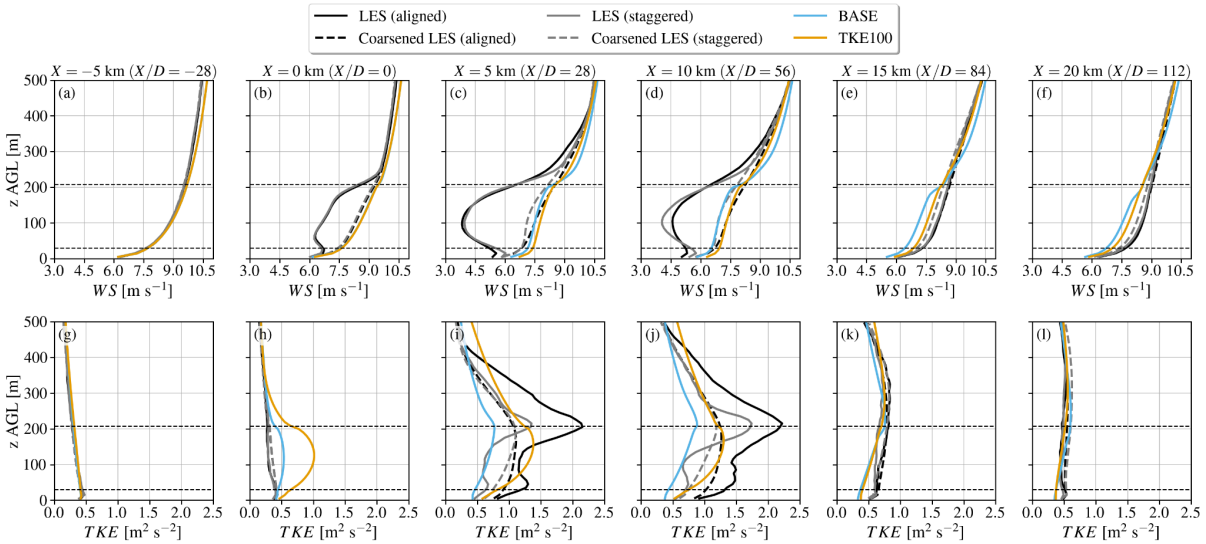

Figure 10. Vertical profiles of time-averaged wind speed (a--f) and TKE (g--l) at specific streamwise distances X (expressed as X/D in parentheses) probed over the southernmost column of turbines near Y= 0 km. The aligned and staggered layout LES without spatial averaging and NWP-WFP cases BASE and TKE100 are shown. The dashed horizontal lines represent the rotor top and bottom tips.

Minor comments

Referee comment: 1. The inclusion of LES results for the staggered layout is welcome, as it provides an additional perspective beyond the aligned (worst case) configuration. However, treating the staggered layout as an equivalent reference introduces inconsistencies. Throughout the results section, the comparison between WFP and LES focuses primarily on the aligned layout, which yields unfavourable results for the WFP in terms of wind speed, TKE, and power. In several instances, the authors counter these discrepancies by stating that agreement improves when using the staggered LES as a reference. This comparison is not valid, as it involves different layouts.

Such statements should be removed or instead be framed as observations, possibly followed by hypotheses regarding the WFP behaviour. If the authors wish to compare against staggered LES results, then corresponding WFP simulations with a staggered layout are really required. Although the authors may argue that this would not alter the conclusions (which I expect) or that will produce same results as the aligned layout (which I doubt), consistent configurations should be maintained for methodological rigour.

This issue also affects the quantitative statement in lines 383–384: “Subtracting the wind speed change of the two LES with both the coarse and fine NWP-WFP cases, a difference of 0.15–0.60 m s−1 is found.” It appears that the staggered LES may have been used to define the lower bound, which is not appropriate. This statement is also reflected in the abstract (lines 11–12) and should be revised to rely solely on aligned configurations. Affected passages include lines 11–12, 283, 331–334, 344–345, 359, 383–384, and 427–428 (the latter partially makes an observation).

Response: We appreciate the referee's comment. The staggered LES was included to demonstrate how wake recovery depends on turbine layout, not to validate the aligned

NWP-WFP simulations. We acknowledge that this was not clearly stated in the manuscript. Consequently, we have revised the text by removing or rephrasing statements that suggested a direct validation of the NWP-WFP simulations against the staggered LES. When we mention the staggered LES, we present it as an observation about layout sensitivity, highlighting that the spatial distribution of momentum deficit in the coarser Fitch model physically resembles the more uniform wake structure observed in the staggered layout. This is an important result of the staggered LES.

We have also revised the quantitative wind-speed differences reported in the Abstract and Results to be based exclusively on comparisons between the aligned LES and the corresponding aligned NWP-WFP simulations. Specifically, the wind-speed difference reported in the Abstract and Results has been updated to [0.15–0.50] m s^{-1}, based solely on the aligned LES comparison. These revisions affect the Abstract and the former lines 283, 331–334, 344–345, 359, 383–384, and 427–428.

Referee comment: 2. Upon re-reading, Section 3.2 is not sufficiently convincing in its current position. The discussion there requires prior context on wake behaviour and TKE distributions from both WFP and LES simulations to interpret the power results. At this stage, concepts such as near-farm wakes and farm-induced TKE have not yet been introduced, but they are used in that section. I suggest moving this section later in the manuscript, for example after Section 3.3, once the wake dynamics have been described.

Response: We thank the referee for this useful suggestion. We agree that presenting the wake flow fields and TKE distributions before the turbine power results improves the logical flow of the Results section. The key concepts used in the power discussion, including wake-deficit structure, the wind farm exit as a reference point, and the role of farm-induced TKE in intra-farm recovery, are introduced in Section 3.3 on the wake flow field. We have therefore moved the former Section 3.2 (row-averaged streamwise power patterns) to directly follow Section 3.3, so the power results can be interpreted in the context of the wake structure and TKE distributions already introduced.