Response to reviewers' comments (2)

Paper title: "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

Reviewer #2

The authors are praised for conducting additional simulations and rephrasing several of the previous exaggerated statements. The manuscript has improved significantly.

Thank you for your support of our work.

The fundamental issue remains about the term “under-resolved gradient”. The authors insist that this interpretation of their results is correct, but, as also another reviewer pointed out and as I discuss further below, this term is misleading and inaccurate and therefore it should be removed from the manuscript. The title could be changed to simply: “Slow wake recovery and low turbulence behind wind farms parameterized in mesoscale simulations”. Any use of, or reference to, the term or concept of “under-resolved gradients” must be eliminated if the manuscript is to be considered for publication any further.

We thank the reviewer for pointing out the potential ambiguity associated with the term “under-resolved gradients” and for emphasizing the importance of a clear conceptual framing of the slow wake recovery problem. After careful consideration of this comment, we have revised the manuscript accordingly.

The term “under-resolved” was removed from the title, which is now “Slow wake recovery and low turbulence behind wind farms parameterized in mesoscale simulations”. We have also removed this term from the manuscript as a whole. More emphasis is put on the fundamental issue, which is the representation of the wind farm wake effects by the WFP on an inherently coarse mesoscale grid.

We clarify that the weaker spatial gradients in wind speed in the mesoscale simulations influence wake recovery in three ways: (i) directly through Eqs. (1) and (2); (ii) indirectly by the reduced shear production of TKE. However, we now emphasize that this is only the physical mechanism through which the slow wake recovery manifests, and an intermediate agent, not the fundamental cause of the problem.

Finally, we note that previously identified inconsistencies in the discussion, such as the interpretation of the role of weaker gradients or the apparent absence of slow wake recovery within the wind farm, have been addressed through revisions to the text. These changes improve clarity and consistency without altering the underlying physical interpretation.

I bring forward three examples (from the reply) that illustrate that the concept of under-resolved gradients is bogus in the revised manuscript.

1. “[under-resolved gradients are] a feature that occurs mostly outside the grid cells where the WFP acts, downstream of the wind farm. “Under-resolved gradients” refer to how the wake behind a wind farm is represented in a mesoscale grid and the consequent impacts on wake recovery compared with the LES.”

The authors insist that the term is appropriate but now their new arguments become contradictory and inconsistent. This is the first time that they mention that the term “under-resolved gradients” refers to the grid cells OUTSIDE and DOWNSTREAM of the wind farm; this was never explained in the original paper. However, this re-definition now implies that under-resolved gradients do not occur and/or are not relevant in the grid cells INSIDE the wind farm, which is instead where the gradients are the most unresolved!

We thank the reviewer for highlighting this inconsistency and for prompting us to clarify this point. We agree that the original wording could lead to confusion.

In the revised manuscript, the distinction between regions inside and downstream of the wind farm was introduced to address comments from other reviewers, but it was not expressed clearly. Our intent was not to imply that weaker or poorly represented gradients occur only downstream of the wind farm. Rather, we meant that their effects on wake recovery are <u>most discernible</u> in the near-farm wake, where momentum extraction by the turbines no longer occurs and wake recovery can be evaluated in isolation.

Within the wind farm, momentum extraction and wake recovery occur simultaneously, making it difficult to separate their individual contributions. Downstream of the wind farm, only wake recovery remains, which allows for a clearer assessment of the processes controlling it. This distinction motivated the separation between intra-farm and downstream analyses, although we acknowledge that the original wording did not reflect this correctly.

To address this issue, we have revised the text throughout the manuscript. For example, the statement:

Original: “This slower wake recovery occurs predominantly in the near-farm wake, a region that lies outside the direct influence of the WFPs and is therefore governed by grid-resolved dynamics and planetary boundary layer (PBL) schemes.”

has been replaced with:

Modified: “This slower wake recovery is most discernible in the near-farm wake, where momentum extraction by the turbines no longer occurs. Within the wind farm, momentum extraction and wake recovery occur simultaneously and cannot be distinguished in the current analysis. Therefore, the near-farm wake lies outside the direct influence of the WFPs and is instead governed by grid-resolved dynamics and planetary boundary layer (PBL) schemes.”

Similarly, we revised earlier statements to clarify that slow wake recovery may also occur within the wind farm but is less discernible due to the concurrent momentum extraction. For instance:

Original (L79): "Because the slow wake recovery and the abrupt TKE decrease in the NWP-WFP occur in downstream cells without turbines, they may not be caused by the WFP."

has been replaced by:

Modified: "A slow wake recovery may also exist within the wind farm; however, because it occurs simultaneously with turbine momentum extraction, it is less discernible there. "

These revised statements are in accordance with other statements from the original manuscript, such as (L350):

"The momentum extraction by the turbines ceases in the near-farm wake region so that the wake recovery rates can be evaluated in isolation."

We have made similar corrections throughout the manuscript to ensure consistency. These revisions resolve the issue as one of wording and clarity, rather than a physical inconsistency in the interpretation.

2. "We agree that when gradients are evaluated using WRF-scale differencing, locally large instantaneous gradients can occur in the mesoscale model, sometimes exceeding those diagnosed from the coarsened LES."

I already pointed out in my previous review that their own results show that sometimes the gradients are actually over-resolved, not under-resolved, by the mesoscale model. The authors state that these cases are not "spatially coherent" and not "organized" and therefore do not generate enough turbulence via shear. This is not true because the patterns are actually well organized and the shear generation must be large in the presence of such strong resolved gradients. If the mesoscale model sometimes generates under-resolved gradients but sometimes it generates over-resolved gradients, it means that the concept of under-resolved gradients is not universal and not always applicable in the presence of a WFP.

Thanks for pointing out this apparent inconsistency in the comparison of gradients between the mesoscale simulations and the coarsened LES.

We agree that the statement above can be misleading. It is important to keep in mind that the coarsened LES results shown are high-resolution LES data that are coarsened (averaged) in post-processing, and not an LES performed on a coarse grid.

The wake recovery physics observed in the coarsened LES still correspond to the gradients and momentum fluxes in the LES at its native (non-averaged) resolution. The coarsened LES is only used as a diagnostic for comparison and does not represent the actual dynamics driving wake recovery.

For this reason, comparing gradients from the coarsened LES with those from the mesoscale simulations is not appropriate for interpreting differences in wake recovery. When the comparison is made against the native-resolution LES, the spatial gradients in the mesoscale simulations are consistently weaker within the wind farm and in the near-farm wake (Fig. 9b,c).

In the revised manuscript, we clarify that the comparison with coarsened LES serves only to evaluate streamwise changes in wind speed and TKE in the wind farm wake. Likewise, the non-averaged LES is used to compare the gradients. The following is included in lines 426–434:

"In this section, we examine two aspects of the comparison between the LES and the NWP-WFP BASE and TKE100 cases. First, we evaluate how the non-averaged spatial gradients in the LES influence wake recovery, and how the horizontal and vertical gradients in the non-averaged LES compare with those from the NWP-WFP simulations. Second, the coarsened (averaged) LES is used to evaluate the streamwise evolution of wind speed and TKE in the wind farm wake and compare it with the NWP-WFP cases. The wake recovery physics observed in the coarsened LES still correspond to the gradients and momentum fluxes in the LES at its native, non-averaged resolution. The coarsened LES is only used as a diagnostic for comparison and does not represent the actual dynamics driving wake recovery."

3. "A potential path forward is the development of a subgrid model that accounts for the missing spatial gradients driving wake recovery."

This is a troublesome recommendation, because, again, it implies that these under-resolved gradients are the problem to address, whereas they may be (at times) the consequence of the limitations of the WFPs. A sub-grid model should not try to generate sub-grid gradients, but sub-grid wakes. This is another example of how under-resolved gradients are treated as the cause of the problem, as opposed to a manifestation of one.

Thanks for pointing this out. We agree that the original wording could be interpreted as treating spatial gradients as the root cause of the problem rather than as a manifestation of the underlying limitations of the mesoscale representation.

In response, we have revised the discussion of future work to make it more general and to focus on the problem rather than on a specific form of the solution. In

particular, we removed the suggestion of explicitly modeling subgrid gradients and instead emphasize the need to improve the representation of wake recovery processes more broadly.

Specifically, the original text:

Original: “A potential pathway forward is the development of a subgrid model that accounts for the missing spatial gradients driving wake recovery. Such a model would act over grid cells downstream of the wind farm in the near-farm wake and be evaluated against LES, potentially using empirical tuning. Otherwise, the underestimation of wake recovery may lead to overestimated wake losses.”

has been replaced with:

Modified: “While refined subgrid wakes and TKE parameterizations may improve intra-farm dynamics, addressing slow near-farm wake recovery downstream remains challenging, as WFPs do not act in this region. Future efforts should focus on improving the representation of shear-driven TKE production and developing approaches that better capture spatial variations in wake recovery across grid cells within and behind the wind farm, as recently demonstrated by García-Santiago et al. (2026).”

This revision avoids prescribing a specific modeling strategy and instead highlights the need for improved representation of wake recovery dynamics, consistent with the reviewer’s comment.

References:

García-santiago, O., Badger, J., Hahmann, A. N., Volker, P. J. H., Ott, S., Laan, P. Van Der, & Kelly, M. (2026). A wind-farm wake-turbulence parameterization for the WRF model. *EGUsphere (Preprint Repository)*, *April*, 1–34. https://doi.org/https://doi.org/10.5194/egusphere-2026-2144

Bottom line: the very concept of under-resolved gradients is obscure and contradictory and should be removed from the manuscript.

We thank the reviewer for this comment and for emphasizing the importance of clear terminology. In response, we have removed the term “under-resolved” from the manuscript and instead focus on the underlying limitation associated with the coarse grid resolution of the mesoscale simulations.

Reviewer #3

The manuscript has been improved in several important aspects. The content of the original submission was already sufficient for publication; the main issues concerned the framing of the topic, the alignment between the results and the stated claims, and clarity in the wording. The revised version now presents a more accurate and focused study: the title, abstract, and narrative have been updated and are better aligned with the analysis and results.

In addition, the authors conducted new simulations that further support the revised research focus and lead to an interesting and important conclusion: Even when subgrid layout effects or TKE adjustments are included to mimic the horizontally averaged LES within turbine cells, the mesoscale-WFP simulations still exhibit slower wake recovery in downstream (where WFP are inactive) cells than the LES. This is a valuable finding with meaningful implications for the community relying on these parameterizations.

The authors have addressed my first round comments thoroughly, and I am satisfied with their responses. Below I provide a few very minor comments aimed purely at improving clarity. All line numbers refer to the diff LATEX version provided.

We thank the reviewer for the positive assessment of the revised manuscript and for recognizing the improvements in the alignment between the framing, results, and conclusions. We are also glad that the additional simulations and the resulting findings are considered valuable.

We have incorporated the reviewer's minor comments to further improve clarity in the manuscript.

Minor comments

1. Line 208: It would be helpful to explicitly state at this point that MAV does not include axial induction (you clarify this later, but it belongs here). Lines 222–227: Please restate that MAV is only tested for the aligned layout. Although line 212 notes that all NWP–WFP simulations use the aligned layout, I expected MAV to be tested also for the staggered layout since it can also perform the those layout and you have the LES of the case.

Thanks for pointing this out.

We have clarified the description of axial induction earlier in the text. The revised sentence now reads:

"The wind farm is represented using the Fitch \citep{Fitch2012} and MAV \citep{Ma2022a,Ma2022b} WFPs with TKE advection enabled \citep{Archer2020}. The Fitch WFP includes an axial induction modification following \citet{Vollmer2024}."

We have also added an explicit statement that MAV simulations are only performed for the aligned layout:

"To investigate the role of subgrid wake effects on wake recovery, we additionally implemented the "MAV" wind farm parameterizations \citep{Ma2022a,Ma2022b}, ported from the standard release of WRF v4.6. The MAV WFP is based on the analytical wake model of \citet{Xie2015} and represents wake overlap through a superposition of hub-height wind speed deficits \citep{Ma2022b}. In contrast to the Fitch scheme, which relies on grid-cell-averaged momentum extraction, MAV explicitly accounts for subgrid wake interactions and has been shown to improve turbine power predictions when compared against offshore SCADA data \citep{Ma2022b}. Similarly to the Fitch-based simulations, the MAV-based simulations only consider the aligned layout scenario."

We agree that applying MAV to the staggered layout would be of interest, particularly in terms of momentum extraction and power predictions. However, the focus of this study is on wake recovery downstream of the wind farm, which we find to be only weakly sensitive to the choice of WFP (including MAV). For this reason, we limited the MAV simulations to the aligned layout.

2. Lines 293–298: This passage is currently confusing and would benefit from rewording. 1) You are not presenting wake losses per se. 2) The Fitch WFP does not spatially average wind-speed deficits over grid cells; instead, it applies a momentum sink over the volume cell proportional to the rotor area, which acts as a "smearing'' when applied into the tendencies.

Thanks for the clarification.

> **Regarding point 2.1), we agree that we are presenting power rather than wake losses. We have therefore reframed the paragraph to reflect this more clearly. While the link between wake effects and turbine power is evident (e.g., Fig.~4a, where mesoscale simulations show higher power than the LES), we avoid referring to these results as wake losses.**
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> **Regarding point 2.2), we have also revised the description of the Fitch WFP to more accurately reflect its formulation, following the reviewer's comment.**
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> **The original text:**
>
> **"In summary, the coarser NWP-WFP configurations, the Fitch WFP spatially averages the wind speed deficit over each grid cell, leading to an underestimation of wake losses at downstream turbines and a corresponding overestimation of power. This excess power implies enhanced momentum extraction within the wind farm, which modulates the wind speed at the farm exit. The MAV scheme mitigates this behavior by explicitly accounting for subgrid turbine-turbine wake interactions, resulting in more realistic wake losses and power levels. As a result, the wind speed at the wind farm exit, which is critical for downstream wake recovery, is more accurately represented when subgrid wake effects are included."**

has been replaced with:

"In coarser NWP-WFP simulations, the WFPs apply the turbine-induced momentum sink over the grid cell volume, which effectively smooths the wind speed deficit within the cell. This representation leads to weaker local deficits at downstream turbines and consequently higher power production. The associated increase in turbine-induced momentum extraction influences the wind speed at the wind farm exit. The MAV scheme mitigates overestimated momentum extraction by accounting for subgrid turbine–turbine wake interactions, resulting in more realistic power levels and wind farm exit wind speeds. As a result, the inflow to the near-farm wake is more accurately represented when subgrid wake effects are included."

2.3) Phrases such as "wind speed at wind-farm exit'' refer to features the reader has not
encountered yet; up to this point only power has been shown. 4) The same applies to references to "enhanced momentum" with "modulates the wind speed," which are unclear in context. You latter described it.

Thank you for pointing this out. We agree that these references were introduced before being properly explained, which could hinder readability.

To address this, we added a brief explanatory paragraph before interpreting the results of this section, introducing the concepts of momentum extraction, wake recovery, and their link to the wind speed at the wind farm exit.

The original text:

"In summary, the coarser NWP-WFP configurations, the Fitch WFP spatially averages the wind speed deficit over each grid cell, leading to an underestimation of wake losses at downstream turbines and a corresponding overestimation of power. This excess power implies enhanced momentum extraction within the wind farm, which modulates the wind speed at the farm exit. The MAV scheme mitigates this behavior by explicitly accounting for subgrid turbine-turbine wake interactions, resulting in more realistic wake losses and power levels. As a result, the wind speed at the wind farm exit, which is critical for downstream wake recovery, is more accurately represented when subgrid wake effects are included."

has been replaced with:

"Variations in turbine power are explainable by understanding the energy balance within the wind farm. The kinetic energy of the wind that is converted into turbine power (momentum extraction) is resupplied by turbulent transport towards the wind farm and its wake in the vertical and lateral directions (momentum/wake recovery) (Vermeer et al., 2003; Stieren and Stevens, 2022).

The relation between momentum extraction and wake recovery within the wind farm thus dictates how much kinetic energy is available at the wind farm exit.

In coarser NWP-WFP simulations, the WFPs apply the turbine-induced momentum sink over the grid cell volume, which effectively smooths the wind speed deficit within the cell. This representation leads to weaker local deficits at downstream turbines and consequently higher power production. The associated increase in turbine-induced momentum extraction influences the wind speed at the wind farm exit. The MAV scheme mitigates overestimated momentum extraction by accounting for subgrid turbine–turbine wake interactions, resulting in more realistic power levels and wind farm exit wind speeds. As a result, the inflow to the near-farm wake is more accurately represented when subgrid wake effects are included."

3. Line 344: Please clarify the phrase "the momentum extraction by the turbines acts simultaneously with the wake recovery." If this refers to LES, note that extraction occurs at the rotor while recovery occurs downstream. What is the intended meaning? Is it referring the mesoscale-WFP simulations?.

Thank you for pointing this out. We agree that the phrasing was unclear.

While momentum extraction occurs locally at the turbine rotors, it is common in the literature to describe the wind farm as a control volume, within which kinetic energy is modified by both internal sinks and fluxes across its boundaries. From this perspective, turbine-induced momentum extraction and wake recovery—through lateral and vertical momentum fluxes—act simultaneously to modulate the flow within the wind farm.

Here, we use this control-volume interpretation in a conceptual sense to describe the mechanisms affecting the flow within and downstream of the wind farm. This interpretation applies to both the LES and the mesoscale-WFP simulations.

We have revised the wording in the manuscript to clarify this point.

The original text:

"In the intra-farm wake region, the momentum extraction by the turbines acts simultaneously with the wake recovery."

has been replaced with:

"From a control-volume perspective of the wind farm, momentum extraction and wake recovery act simultaneously within the intra-farm region, although at the turbine scale extraction is localized at the rotor and recovery occurs downstream."

4. Lines 354–355: This appears to be a LATEX compilation error and should be corrected.

The lead author and co-authors have all reviewed the manuscript as well as the tracked changes manuscript and do not see a LaTeX compilation error on those lines, unfortunately.

5. Line 452: This sentence requires minor rewording. As written, it suggests that the LES attempts to match the mesoscale simulations, which is not the intended meaning.

Thank you for pointing this out. We agree that the original phrasing could be misinterpreted.

The original sentence:

"The stronger momentum extraction in the staggered LES, relative to the aligned LES, results in improved agreement with the BASE and TKE100 cases."
has been replaced with:

"Stronger momentum extraction occurs in the staggered LES relative to the aligned LES. Therefore, cases BASE and TKE100, which overestimate momentum extraction, show better agreement with the staggered LES."

6. Figure1: You forgot changing the word "decay" in panel (f)

We thank the reviewer for pointing this out. We replaced "fast TKE decay" with "low turbulence" in panel (f) for consistency with the revised title and terminology used throughout the paper.

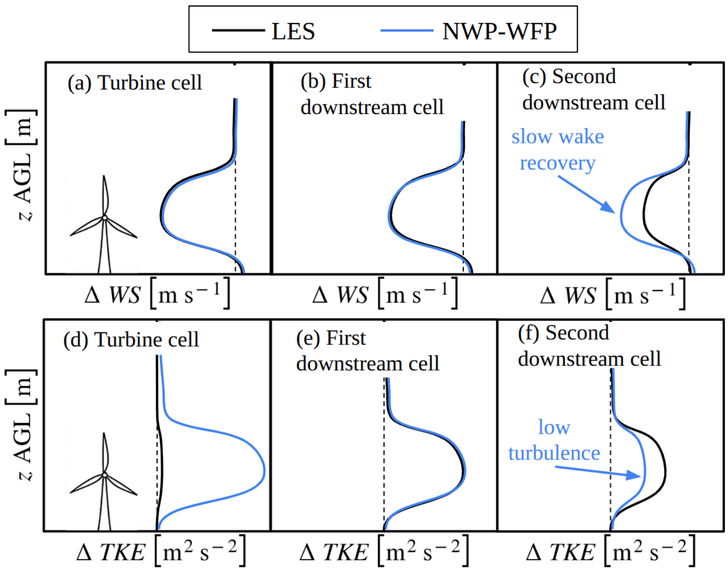

Figure 1 (modified).

7. Abstract (optional suggestion): Consider including the numerical differences between

LES and mesoscale simulations in the far wake. Since the far-wake region is where mesoscale-WFP approaches are expected to perform best, these values may help highlight more the practical relevance of the results.

We thank the reviewer for this helpful suggestion. We agree that the far-wake region is particularly relevant, especially in the context of inter-farm wake interactions over large distances.

In the original version, we did not include far-wake biases in order to emphasize where they originate, namely in the near-farm wake. In the revised abstract, we now report both near- and far-wake wind speed biases, and additionally quantify the contribution of slow wake recovery to the near-farm bias.

The abstract was also revised following comments from the other reviewer. The updated version now includes the far-wake bias (0.4--0.6~m~s^{-1}) alongside the near-farm bias and clarifies their relationship.

The original text:

“Numerical Weather Prediction (NWP) and climate models equipped with Wind Farm Parameterizations (WFPs) can simulate cluster wake effects affecting downstream wind farms in both onshore and offshore environments. This study evaluates the wake recovery behind a wind farm represented by the NWP-WFP approach in the Weather Research and Forecasting (WRF) model using either the \cite{Fitch2012} or \cite{Ma2022a,Ma2022b} WFPs. Results are benchmarked against large-eddy simulations (LES) of an idealized offshore wind farm with aligned and staggered layouts under neutral atmospheric stability. The near-farm wake recovery is underestimated in NWP-WFP simulations because of two interconnected issues. First, the spatial gradients in the wind velocity field within the near-farm wake are necessarily under-resolved at mesoscale grid resolutions compared to the LES. Second, the low turbulence kinetic energy (TKE) in the near-farm wake in the mesoscale simulations is not due to excessive dissipation, but rather to insufficient shear production of TKE caused by these under-resolved gradients. As a result, a wind speed bias of approximately 0.15–0.60~m~s^{-1} develops in the near-farm wake, depending on the simulation setup and wind-farm layout. Although this behavior is confined to a short downstream distance, it has lasting consequences for the far wake region. Furthermore, the slow near-farm wake recovery is not caused by a limitation of the WFP itself, but by the representation of inherently fine-scale processes on a coarse mesoscale grid. These results underscore the need to address under-resolved spatial gradients to improve wake recovery and reduce far-wake biases in NWP-WFP simulations.”

has been replaced with:

Modified: “Numerical Weather Prediction (NWP) and climate models equipped with Wind Farm Parameterizations (WFPs) can simulate cluster wake effects affecting downstream wind farms in both onshore and offshore environments. This study evaluates wake recovery behind a wind farm represented by the NWP-WFP approach

in the Weather Research and Forecasting (WRF) model using either the \cite{Fitch2012} or \cite{Ma2022a,Ma2022b} WFPs. Results are benchmarked against large-eddy simulations (LES) of an idealized offshore wind farm with aligned and staggered layouts under neutral atmospheric stability. Near-farm wake recovery is underestimated in NWP-WFP simulations due to its representation on a coarse mesoscale grid. This limitation leads to slow wake recovery through two interconnected mechanisms: (i) spatial gradients in the wind velocity field are underestimated compared to LES, and (ii) turbulence kinetic energy (TKE) remains low not because of excessive dissipation, but due to insufficient shear production caused by these weakened gradients. Depending on the simulation setup and farm layout, a wind speed bias occurs in the near-farm wake (0.3--1.3~m~s^{-1}) and persists into the far wake region (0.4--0.6~m~s^{-1}). Slow wake recovery contributes approximately 0.15--0.60~m~s^{-1} to the near-farm bias, while momentum extraction and recovery processes within the farm also play a role. The slow wake recovery is not caused by limitations of the WFPs themselves, as it also occurs outside their region of influence, and adding subgrid wake effects does not significantly impact recovery. Rather, the slow wake recovery is a consequence of mesoscale flow representation. This behavior is not limited to regions downstream of the wind farm but is less visible within the farm, where wake recovery occurs simultaneously with turbine-induced momentum extraction. These results highlight the need for improved representations of wake recovery both within and downstream of wind farms. While enhanced subgrid modeling, shear-driven TKE production, and refined WFP formulations may improve intra-farm dynamics, accurately capturing near-farm wake recovery downstream remains challenging, as WFPs do not act in this region.”