Responses to Reviewers' Comments

on the manuscript entitled ' Inclusion of the subgrid wake effect between turbines in the wind farm parameterization of WRF ' submitted to Geoscientific Model Development .

We sincerely thank the editor and two reviewers for their very constructive comments and suggestions, which helped us to improve our manuscript significantly. We made necessary modifications to address all of concerns raised by two reviewers in the revised manuscript where the changes are highlighted. Major modifications of our manuscript include:

1. The CFD experimental part has been expanded to include validation of single turbine wake simulation results against measured results and introduction of double turbine wake experiments (Section 3).
2. We have updated the version of the WRF to 4.3 and repeated the previous experiments (Section 4).
3. We have updated the organization of the manuscript and rewrite some sections.

Responses to Reviewer 1:

The authors describe a modification to the default Fitch wind farm parameterization (WFP hereafter) in the WRF model to incorporate the sub-grid wakes between turbines that are located in the same grid cell. The WFP is based on the Jensen linear expansion wake model and accounts for (or claims to account for) the wake overlapping and for the angle between the wind direction and the rows and columns of turbines in a wind farm with a regular layout. The WRF model is then run for 3 days with an incredibly huge wind farm consisting of 25600 turbines of 3 MW each (corresponding to an astronomical installed capacity of 76 GW), covering over 100 x 100 km2 offshore of Hong Kong. Sensitivity to grid spacing and turbine spacing is assessed. Results indicate that the proposed modification to the Fitch scheme produces more wind power and more turbulence than the original Fitch scheme, and therefore, somehow, this means that the proposed modification is desirable. Since there is no comparison of the two against any real data, one cannot conclude that the proposed changes are beneficial in any way. This is a fundamental flaw of the paper. In addition, there are several major issues in the way the parameterization was designed, as described below, and the notation is confusing or possibly wrong. The issues are so severe that I cannot recommend publication of the paper at this point.

Thanks a lot for your such careful and detailed comments. We have made a great effort to improve this manuscript under your suggestions. Hopefully most of your concern has been resolved now.

1. If a team wants to demonstrate that their method is better than the default method, then they need to have an observable dataset to compare the results obtained with the old and the new methods. Only by comparison with observations one can possibly conclude that one is better than the other. It is not sufficient to simulate a case with both, as the authors did in this study, because we do not know what the truth is. To make the matter worse, why simulate an impossible farm, one that has more turbines than any built before (25,600) and that has a capacity at least 30 times larger than the largest wind farm existing today and covering an area of approximately 100 km × 100 km?

As the focus of this paper is a large-scale wind farm that is yet to be built, comparing and validating measured data from existing wind farms is not feasible. Although this paper does not utilize the wind farm's measured data to directly validate the new parameterization, sensitivity experiments show that the difference between the original and new parameterization diminishes with the increasing turbine distance, demonstrating a reasonable improvement of the new parameterization scheme. And the CFD experiments are validated by the measured data close to the wind turbine to prove their accuracy. The modified analytical model of the wake flow is validated and corrected by the CFD experiments.

2. The literature review in the Introduction is limited and old, focusing mostly on studies pre-2014. Many more papers have been published since then, including several with the Fitch parameterization. Two relevant studies in particular have been missed and need to be described here because they introduced analytical wake models into WRF to account for the sub-grid wake effects, similar to what this paper is trying to do: Ma et al. (Wind Energy Science, 2022) about the Jensen wake model and Ma et al. (Wind Energy, 2022) about the Gaussian model, Geometric model, among others, and their ensemble.

These references you mention have been added and discussed in the introduction. There are currently four ways to correct the subgrid wake effect between turbines in the WFP of WRF. Pan and Archer et al's (2018) hybrid parameterization scheme based on geometric computation, Ma and Archer's Jensen wake model correction scheme, Xie and Archer's (2020) Gaussian wake model correction scheme, and an ensemble correction scheme that averages the first three. Ma conducted a study and found that the correction schemes presented above performed well, with an overall bias ranging from -11.0% to 21.6% and an overall RMSE between 5.3% and 27.1%. Nonetheless, no individual correction scheme outperformed the others for all wind directions, wind farms, and resolutions.

3. The discussion of Pan and Archer (2018) is incorrect. They used LES results to calibrate the geometric model, which is an analytical model for the wind turbine wakes, and then they inserted it in the WRF model. There is no need to run LES to use it. As far as I know, it was the first published paper that treated sub-grid wakes in a mesoscale model, WRF in fact. Then Ma et al. (2022a,b) also incorporated sub-grid models in WRF. As such, this paper is not really introducing "a new way, namely, through a simple engineering wake model" because this has actually already been done and documented. The literature review therefore needs to be slightly rewritten to give proper recognition to the three past studies mentioned above: Pan and Archer (2018) and Ma et al. (2022a,b).

Thank you very much for your comments. We have cited the researchers mentioned and restructured the section accordingly.

Here is the revised version of the text.

"Pan and Archer et al. (2018) combined the simulation results of LES with the relevant geometric parameters of wind farm layout, and proposed a "hybrid parameterization" scheme. The geometric model was calibrated using the LES results and subsequently integrated into the WRF model and experimental results show that the hybrid parameterization scheme also has a good effect on the correction of subgrid wake effect.

Ma et al. (2022a,b) also incorporated sub-grid models in WRF. They carried out comparative experiments on four schemes: a hybrid parameterization scheme for geometric calculations, a Jensen wake model correction scheme, a Gaussian wake model correction scheme, and an ensemble correction scheme that combines the first three using averaging. All of the correction schemes presented above performed well, but no individual correction scheme outperformed the others for all wind directions, wind farms, and resolutions."

We present a hybrid parameterization scheme based on geometric computation, proposed by Pan and Archer et al. (2018), combined with the Jensen wake model correction scheme proposed by Ma and Archer et al. (2022). Meanwhile, the Ma and Archer et al. (2022) proposal for the Jensen wake model correction scheme only includes wind turbines with an upwind direction of ±30° and distance less than 20D or less in the wake superposition, whereas this paper's analysis does not impose such limitations.

4. Also, there was a code bug in WRF that affected the results of the Fitch parameterization, documented by Archer et al. (MWR, 2020). Which version of the WRF was used here? If between 3.6 and 4.2, then the simulations need to be redone to fifix the bug.

Thank you so much for your suggestion. Regrettably, our simulation runs on version 3.9 of WRF. To rule out the possibility of bugs by the old WRF version, we have updated the version of the WRF to 4.3 and repeated the previous experiments, and we now have significantly more reasonable results than before.

5. Eqs. 1-3 are incorrect. They are the same as in the original paper by Fitch et al. (2012), but this is not how the scheme is actually implemented in the WRF model. Archer et al. (2020) mentioned above shows the correct version of the equations as they are implemented in WRF since v3.6. Noticeably, the thrust and power coefficients are a function of hub-height wind speed only, not of V_{ijk} (there is only one C_p and one C_t for the turbine, not one for each vertical level k). Also, it is not the wind vector squared that is used for the wind speed tendency. Lastly, A_{ijk} is not the swept area, it is the portion of the swept area that is in vertical level k.

Equations (1) to (3) have been replaced with:

To obtain the vertical distribution of TKE and velocity, the basic principle is that each vertical level k that intersects the rotor contributes proportionally to the fractional rotor area contained in that level A_k and to the horizontal wind speed at that level U_k:

$$\frac{\partial \text{TKE}_k}{\partial t} = \frac{1}{2} \frac{A_k C_{\text{TKE}} U_k^3}{(z_{k+1} - z_k)}, \tag{3}$$

$$\frac{\partial u_k}{\partial t} = -\frac{1}{2} \frac{A_k C_T U_k u_k}{(z_{k+1} - z_k)}, \quad \text{and} \tag{4}$$

$$\frac{\partial v_k}{\partial t} = -\frac{1}{2} \frac{A_k C_T U_k v_k}{(z_{k+1} - z_k)}, \tag{5}$$

where u_k and v_k are the horizontal wind components and z_k is the height of vertical level k. Equations (3)–(5) are multiplied by a correction factor if energy conservation is not met across the rotor. If multiple turbines are present in the same grid cell, each will add the exact same contribution to the TKE and momentum tendencies as in Eq. (3)–(5).

The wake shading coefficient's solution process assumes that the wind farm is orientated parallel to the latitude and longitude. The wind farm's vast size has resulted in many grids within the wind farm area. This assumption only affects the grids on the periphery and has no bearing on the inner grids, thus the error of this assumption is limited for a large wind farm where the sub-grid wake effect is notable. And one could narrow the grid size to avoid the inconvenience associated with this assumption. More importantly, the angular correction coefficient and the expansion correction coefficient have been calculated in this paper using CFD experiments. This ensures that the incoming wind speed of each turbine can be accurately calculated, even when the wind farms are not arranged in an east-west or north-south direction. The calculations are based on the wake of the front turbine combined with superposition effect of the wake, rather than on the layout of the wind farm. Therefore, we believe that the new parameterization scheme can still work relatively well in modern wind farm layout schemes.

The subscript 'n' in this context refers to the number of the turbine, rather than the total number of turbines. The reason for not using the subscript 'j' is to avoid confusion, as the subscripts 'i' and 'j' are already used to indicate the horizontal position of the grid. vn0 and vnθ are computed using the geometric shading-based wind farm model specified further down.

v(i,j) refers to the magnitude of wind speed of turbine i at turbine j and is not a vector. We apologize for any confusion caused by the expression. However, **V** in this context does not represent a tensor. Instead, it denotes the influence of the front wind turbine on each other turbine in the unit grid (Eq. 5).

The incoming wind speed of each turbine, $v(i,i)$, is determined after the preceding turbine effects are taken into account. The wind speed of the current grid, u_0, varies depending on the location of the grid.

R refers to the radius of the turbine, while $R(i, j)$ refers to the radius of turbine i's wake at turbine j. The two meanings are distinct. However, there appears to be a deficiency in the work carried out as we have not achieved consistency with the prior velocity representation in relation to the shading radius (according to the comment from reviewer 2). Currently, i has been harmonized as the turbine of interest while j is the turbine that produces the effect.

The details of the CFD experimental section has been added (L. 283-330). We regret that we could not include this part of the work previously. However, this section has undergone considerable effort and has been verified with actual radar wind measurement data. As the RANS method is utilized, the velocities displayed in Figure 6 are representative of the time-averaged concept. These results may differ from those of the time-averaged simulation conducted using the LES method. It is important to note, however, that this only represents a portion of our research. In reality, we computed the RANS outcomes for the blade at six different angles and collated an average to achieve a desirable outcome in the end.

0°   30°   60°   90°   120°   150°

We have updated the version of the WRF to 4.3 and repeated the previous experiments.

• Version 4.3 of the WRF has been utilized to re-run the experiment, and the new outcomes are assessed. The analysis now uses the time-averaged outcomes for the last six hours of the simulation, rather than the snapshot results. From our current results, the total power of the wind farm is now closer to the expected under the original and new parameterization schemes, but the spatial distribution of the power is different. In the back row grid of the wind farm, the total power in the new scheme is lower than in the original scheme due to the added wake effect, which is realistic. However, at the right edge of the wind farm, the power at the edge of the grid is slightly higher than in the original scheme due to the higher incoming wind speed calculated in the new scheme, even though the wake effect is taken into account.

• The low wind power output stems from the wind farm's large size and the subsequent wake impact on internal turbines from turbines at the edge. This lowers the internal turbine output and ultimately affects the total power output. Perhaps if not every neighboring grid in this wind farm had turbines set up, but instead there exists a portion of the grid where no turbines are set up to provide some space for wake recovery, the normalized power of the whole wind farm would be much higher.

• We have already addressed this question in the first point. For reference, we provide results for a more extensive area (Figure 12). It has been discovered that the new parameterization scheme does, in fact, decrease the extraction of wind kinetic energy within the wind farm area. As a result, this effect impacts the downstream portion of the wind farm, leading to an increase in downstream wind kinetic energy. The observed phenomenon is not solely attributable to the decrease in turbine power, as the power shift within the wind farm is negligible in the updated findings. It seems that the downstream alteration is more likely a result of heightened turbulent kinetic energy comparing to the original parameterization. This enhances the entrainment of momentum in the wake and upper atmosphere, in other words, strengthens the turbulent transport process of mean kinetic energy from the ambient region to the wake region.
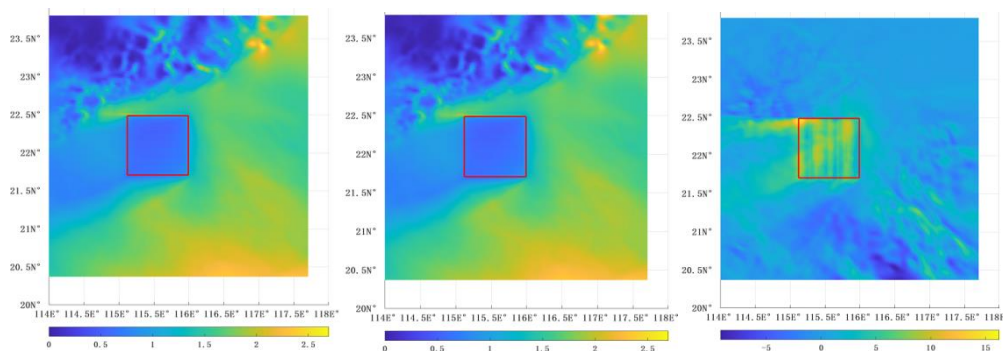

Figure12 Comparison of wind energy distribution in wind farm area for (a) the new parameterization scheme; (b) the original parameterization scheme; (c) their difference.

Minor Remarks

14. L. 12: Please replace "explosive" with a more appropriate adjective.

Corresponding expressions have been modified. (L. 12-13)

15. L. 14: There should be no citations in the abstract, remove the citation Fitch et al. (2012).

Accepted and revised. (L. 15)

16. L. 15: The sentence does not read well, rephrase to something like: "shortfalls, e.g., it does not consider the wakes behind wind turbines inside the same grid cell."

Many thanks for your suggestion. We have revised the sentence. (L. 16-18)

17. L. 22: You need to spell out "CFD"

Accepted and revised. (L. 22)

18. L. 31-34: I know this is probably a translation issue, but the first three sentences have a lot of words but really do not say much ... consider removing them or combining them into one, concise, and clear sentence that goes straight to the point.

Thank you for your comments. We rewrite this one sentence to make it more concise and to the point. (L. 34-36)

Thank you for your suggestion. This is indeed a more appropriate expression and we have made the substitution. (L. 42, 45)

Thank you for your advice and we have adopted the expression you suggested. (L. 41-42)

Many thanks for your suggestion. We have removed the citation to their paper. (L. 45)

Thank you for your suggestion. We have removed the citation to their paper. (L. 48)

Many thanks for your suggestion. This is indeed a paper we do not read. However, our research group has uncovered that offshore wind farms' influence on precipitation is more intricate and can be instigated by topographic effects downstream in the region.

Thank you for your suggestion. We have revised this part. (L. 57)

Accepted and revised. (L. 93-95)

Many thanks for your suggestion. As we mentioned in the fifth reply, we rewrote Eq. 1-3. (L. 103-105)

27. Eq. 7: comparing Eq. 5 and Eq. 7, it appears that i is the turbine of interest and j is one of the n turbines upstream (also from the summation index in Eq. 9). Thus I would call this u_{ij} (not u_{ji}), the wind speed at i caused by turbine j, and I would replace x_j with x_{ij}, the along-wind distance between i and j. Later, L. 218, you define γ_{ij} as the shielding factor from turbine i to j, the exact opposite convention.

Thank you for your suggestion. The corresponding section subscripts have now been adjusted to make them consistent. (L. 216, 219, 220, 227)

28. Figure 9: What value is used to normalize? u_0? Or inflow u_i?

Wind speed is normalized by u_0 and we provide additional explanations in the text. (L. 347)

29. For Figs. 11-13, I would not use a smooth shaded contour plot, but rather a gridded plot, to see better the individual grid cells. Also, using a color like a greenish blue for the near-zero values makes it hard to tell where the difference is positive and where negative. Use white for near-zero instead. Last, use a finite number of color levels, 8-9, and choose the levels in a smart way (e.g., we do not want a plot to be all blue except for with a few grid cells that are other colors, we want to see a balance of cells with the various colors).

Many thanks for your suggestion. We have revised this part and replaced some of the figure. (Figs. 13-15)