Response to Reviewer 1 – WES-2021-7
April 15, 2021

We are thankful to the reviewer for providing the insightful feedback. Please find our response to the comments in blue in the section below.

The study presents numerical simulation runs by the WRF model to investigate recovery processes from an hypothetical 50x50 km^2 offshore wind farm. The WRF is driven by real weather data. The experiments quantify the recovery processes under different wind speeds and wind turbine spacing.

The study is well structured and written, although the language can be improved at some parts. The results are presented clearly, but some figures need be improved to be more accessible to the reader. The discussion picks up on the novel results but also remains very superficial at some points. My main criticism of the study is the neglection of the stability, which is a main control parameter for wake recovery. This is further explained in the comment sections. With the consideration of this aspect and further improvement, the study can be a very valuable contribution to the offshore wind energy community.

General comments

The abstract gives a detailed description of the study, but remains very vague on the results. The results need to be presented more precisely and concretely, (e.g how is high inter turbine spacing defined, densely packed etc…). For more details please see the specific comments.

Thank you for pointing this out. We will make the abstract more clear in terms of results by providing more quantitative information.

My main criticism is that the study does not take into account the stability and boundary-layer height regarding wake recovery. For the description of offshore wind farm impacts on the atmosphere (such as far wake effects/blockage effect or the influence of the farm on vertical turbulent moment flux, as mentioned on p.13 l.24), a consideration of the stability and ABL top (as mentioned in p.10 l.25) as major parameter, along with the park layout and wind speed, have been identified in several recent studies (e.g. Djath et al . 2018, Siedesleben et al . 2018, Cañadillas et al. 2019, Platis et al. 2020 etc…). However, this study only takes turbine spacing and the wind speed into account.

In addition, the results from these mentioned studies and further recent studies about the ongoing investigation of the far field effects of offshore wind farms are not addressed in the study. Also on p.13 l.24: Turbulent vertical mixing depends on the thermal and dynamic stability. Also for strong horizontal wind speed during strong convective conditions vertical recovery may remain the main contributor. Therefore, I highly suggest at least to take the stability (e.g. lapse rate or Richardson bulk number) for the investigated cases into account and include them in the discussion.

This is a very important point. While designing the experiments to study recovery, we wanted to look at wind farm design, specifically, the variability of recovery process under different wind farm spacing and wind speeds. But we agree with the reviewer that the stability question is extremely important. As suggested by the reviewer, we will take an extensive look at the static and dynamic stability patterns of the 3 case studies using lapse rate, Richardson number and other appropriate metrics.

Figures have to be re-worked including units to the scales. For some figures I also recommend to enlarge them to make them more readable. Also the range of the scale hat to be rearranged as e.g in figure 6 a) the variation is seen hardly.

We understand the reviewer's concern regarding the figures. We will replot the figures to make them easier to understand. We will add units to the scales in Fig. 3, 4 and 6. If we enlarge the figures, we will not be able to fit them in the same panel, making it difficult to compare between cases. Hence, we will replot Fig. 3c and Fig. 6 with RAINBOW type colormap to enhance visual clarity. We will also enlarge the text in the figures to make them legible.

To make things easier for the reader, I suggest to define the mean wind direction as positive x. This will help the reader to compare easier cases A with B and C. This will also help to better distinguished between flow effect parallel and perpendicular to the flow e.g., the interpretation of Figures 3 b) , 4, 5 and 6.

We understand that this could be confusing for the readers. But we prefer to keep the figures unchanged because we want to give the readers a flavor of the fact that these simulations are constrained by observed boundary conditions where the wind directions vary. We have taken the components of meteorological variables along the dominant direction. To help readers understand these figures better, we have added arrows showing the prominent wind directions. We will make these arrows bolder so that the difference in wind direction between the different cases clearly discernible.

Why is the recovery only presented for the wind farm domain (Fig. 6). I expect also far field effects similar to the wake effects to be seen in the vicinity of the wind farm. Also this will give a broader picture of the upwind and downwind effects.

Our primary purpose in this study is to show the recovery in the wind farms. The study was conceptualized with the aim to study how wind speed recovery happens in the wind farm. It is important to study recovery in wind farms because it also has a practical implication. It helps us understand how replenishment of energy allows a spatially large wind farm to function. Far-field effects are no doubt very interesting but beyond the scope of the current study.

Specific comments

p.1 l.14. How is high defined? Narrow spacing? Please be more precise.

In our experiments, inter-turbine spacings range from 0.5 km (densely-packed Case I) to 2 km (sparsely-packed, Case III). We will add this quantitative information on spacing to the abstract.

p.1 l.16: What is meant by can be quantified using low-order empirical equations? Please be more concrete.

We have quantified the vertical recovery using second-order empirical equations. The details are given in section 3.5.2 of the paper. We will modify the statement to make it more concrete.

p. l.17. What is meant by high wind speed. Which range are you referring to?

In this study, apart from the different inter-turbine spacings, we also explored the role of different wind speed ranges over which the wind turbines operate, ranging from lowest wind speed of 3 ms^{-1} to highest wind speed of 18 ms^{-1}. Case A corresponds to low wind speed range and case C represents the high wind speed range. We will add this quantitative information on wind speed to the abstract.

p.2. l.15: What version of the WRF model? Which wind turbine parameterization ? Please rephrase the sentence in the abstract or in the introduction as they are identical.

We used WRF version 4.2.1 and the Fitch et al. (2012) wind farm parameterization for our simulations. We will add the WRF version and turbine parameterization in the paper. We will also rephrase the sentences in the introduction to avoid any duplication.

p.4. l14ff: I suggest to add a figure showing the relation between grid cell and turbine spacing in order to makes things more clear for the reader

We will add a figure showing the locations of turbines within the grid cells to make the relation between grid cell and turbine spacing clearer to the readers.

p. 5 l.15: This is still a simulation, so the term 'realistic' is not appropriate.

We will remove the term 'realistic' from the mentioned sentence.

p.6. l.5: Please introduce here what k,i,j is referring to.

The letters k, i, and j are the location indices in the vertical, zonal and meridional directions. We will explain this in the text.

p.6. l.18:Over which domain are the horizontally averaged? Over the wind farm domain?

The horizontal averaging is over whole of domain 3 from the WRF simulations. We will explain this in the manuscript.

Eq. 8 Please describe what is defined by î and Äµ ?

The symbols î and j are the unit vectors in the zonal and meridional directions, respectively. We will explain this in the manuscript. We are unable understand the second symbol. We assume that it is a typo and the reviewer means j.

p.9. l15: Please give a broader description about the statistical analysis.

We will add a description and reference about the Wilcoxon sign rank test.

Eq. 15: The denominator on the right-hand side of Eq. 9 should contain the unit. I also suggest to write 140m – 28m

Adding units to only one term in the equation will not be appropriate. We think the way we have written the equation with m in the numerator is causing some confusion. We will rewrite this equation using symbols to eliminate any confusion about units.

p.7 l.25 Why small v?

Sorry about the typo. We will correct it in the manuscript.

Fig. 3. The figure is hard to read, especially 3c). Please enlarge the plots and the labels. Please add a unit to the scales. For case A the resolution is way to small to be able to follow the analysis on page. 9. l. 15-16.

As mentioned earlier, enlarging the figures will make it impossible to fit them in the same panel making it hard to compare between cases. We will replot the figure with a RAINBOW type colour scheme for better visibility and add units to the labels.

p.10. l.5: Not true several other studies such as Platis et al. 2018, 2020, Siedersleben et al. 2018 reported a deceleration of up to 40 % in the wake of offshore wind farms.

The values reported in our manuscript are averages. The studies mentioned by the reviewers report maximum deceleration, e.g., Platis et al., 2018, 2020 found a maximum deceleration of 40% and 43% in the wake of offshore wind farms, respectively. However, we could not find any explicit mention of deceleration rates in Siedersleben et al., 2018. We will add this comparison in the text.

p.10 l.25. What is the height of the ABL top?

The ABL top is ~1400 m for Case A and ~1000 m for Case B & C. We will add a line showing the ABL top height in Fig. 4.

Fig. 4. I recommend to mark the area where the wind farm is located.

The wind farm is already marked with a black dashed box in Fig. 4. It is also mentioned in the figure caption. We will make the dashed box that depict the wind farm cross-section bolder for better visibility.

Fig. 4: Case A III. Why is there a deceleration and then an acceleration of the flow between 0-1000 m and at x= 780-850 km?

Please note that the direction of wind flow is from right to left in Case AIII. Hence, the regions with red color between 0-1000 m and at x= 780-850 km indicate deceleration upwind of the farm as seen in all cases. In this particular case, there is an alternating band of white and red. This pattern is perhaps giving the impression that there are alternating bands of acceleration and deceleration. However, the white colored regions do not indicate acceleration. Rather, they denote regions where the signals are not statistically significant. Thus, this pattern actually indicates that the upwind deceleration in case AIII is relatively weak. We will explain this in the text and also add an explanation of the white patches in the figure caption.

Fig. 4 The upwind deceleration seem very impressive. I am wondering whether a too small simulation domain is causing an intensification by boundary reflections? Is there a way to assess this influence ?

The domain is very large, 1500 km X 1500 km with a 50 km X 50 km wind farm in centre. The acceleration is not caused by boundary reflections. We had conducted sensitivity studies with domains of different sizes starting from a 300 km X 300 km domain. We found some wake reflections in the smaller domains but there were no boundary effects with this large domain. We will add this explanation in Section 2.2 of the paper.

Fig. 4 b. Why is a streak pattern visible? Can this be also attributed to artifacts caused by the simulation?

Streak patterns are updrafts and downdrafts induced due to wind farm. We conducted significance tests on the results and plotted only the statistically significant signal to minimize the depiction of random noise.

p.11.9 ff. I do not understand how this argument contributes to case C-I. Please describe more clearly.

We assume the reviewer is talking about p11 L8 because P11 L9 talks about case III. We think this sentence is superfluous. We will remove this so as to no cause confusion.

Fig. 5 I do not understand the meaning of the legend at the second left figure in the first row.

These refer to the synoptic, mesoscale and microscale fluxes calculated using the equations described in Section 2.3.1. We will also clarify this in the figure caption.

Fig .5. The description and argumentation of the results is at some points not very precise.

We will expand Section 3.4 to provide improve our explanation of the pattern of vertical synoptic, mesoscale and microscale fluxes in a wind farm.

p.11. l.17. It would be helpful for the reader just to mention again very briefly the difference between synoptic and micro scale.

We will add a brief description of the scales and refer to the appropriate equations in the text.

p.11 l.8-10. "It is possible that this meso-scale momentum transport aids in the wind farm recovery by making more momentum available for downward mixing by turbulence." This is very speculative. Is there a way to justify it ? Can the variations at different heights be explained?

We agree with the reviewer that this statement appears speculative. Indeed, that is why we have intentionally used the word 'possible' because the evidence for this statement is limited to only case C-I. In Case C-I, the UW mesoscale flux is maximum at ~1500 m altitude showing that the momentum is transferred from above free atmosphere (above the PBL height of ~1000 m) into the boundary layer. In Case C-I, a negative UW mesoscale flux at 1500 m height depict a net downward transport of higher momentum. The mesoscale flux is negligible up to 1000 m (around PBL height in the wind farm) because within the wind farm no vertical mesoscale momentum transport leads to downward transport of momentum rather the downward transport of momentum happens through microscale fluxes. We will expand this entire section to further clarify our point. Moreover, we will also provide detailed explanation of the microscale flux patterns.

Fig. 6: Why does the plots in case of III look much coarser than for I and II ?

The reviewer is absolutely right. In case III, we have a turbine in every other grid cell to ensure a 2 km spacing. The data points in in this case are averaged over 4 grid cells covering 2 km X 2 km. That is why case III looks smoother. We will add this explanation to the text.

Fig. 7a) Why is there such a sharp boundary (jump) at about x= 4x10-3 ? Because of the different cases? This could be mentioned in the text.

Yes, the jump at x= $4x10^{-3}$ is for the different cases. We will mention this in text.

p. 17 l. 11. Please refer to the equation or describe the integration by an separate equation.

We noticed there is a mistake in the text, it should have been section 2.3.1 instead of 2.3.3. As suggested by the reviewer, we will add the equation number for the reader's reference.

p.18 l. 31. What do you mean exactly by synoptic scale effects?

What we meant to say here is that wind farms do not affect any synoptic scale fluxes as evident from section 3.4 Fig. 5. In the mentioned figure, the effect on synoptic scale fluxes by the wind farm is negligible. This is the reason the synoptic scale flux line is not visible in the figure. We will state this more clearly in this bullet point.

Technical corrections

p.2. l.1 ff: Please put the citations in chronological order: Will be done.

p.4 l.9: Please correct: boundary-layer scheme: Will be corrected.

p.4 l.10: Please correct: second-order moments: Will be corrected.

p.6 l.22 typo error 'that': Will be corrected.

Fig. 7 b)-d) Please title the figures with its specific cases. : The specific cases will be added in the figure as titles.

References:

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Cañadillas, B., Foreman, R., Barth, V., Platis, A., Siedersleben, S. K., Bange, J., Lampert, A., Bärfuss, K., Hankers, R., Schulz-Stellenfleth, J.,Djath, B., Emeis, S., and Neumann, T.: Offshore wind farm wake recovery: Airborne measurements and its representation in engineeringmodels, Wind Energy, https://doi.org/10.1002/we.2484, 2019.

Platis, A., Hundhausen, M., Siedersleben, S. K., Lampert, A., Bärfuss, K., Schulz-Stellenfleth, J., Djath, B., Emeis, S., Neumann, T., Cañadil-385las, B., and Bange, J.: Long-range modifications of the wind field by offshore wind parks - results of the project WIPAFF, MetZet, 2020b

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Fitch, A. C., Olson, J. B., Lundquist, J. K., Dudhia, J., Gupta, A. K., Michalakes, J., and Barstad, I.: Local and mesoscale impacts of wind farms as parameterized in a mesoscale NWP model, Mon. Weather Rev., 140, 3017–3038, https://doi.org/10.1175/MWR-D-11-00352.1, 2012.