Response to the second round of comments for WES-2023-33

December 14, 2023

general reply

We want to thank the two referees and the editor for reviewing our revised submission. We are pleased to see that our changes are appreciated and we agree that this has made the work a lot stronger. Here we address the five additional comments that were provided by the referees and the editor.

replies to comments

Comment 1: Validation is done against wind speed but nothing about wind direction. In order to provide a complete understanding into the validity of the models, the authors can reproduce something similar to Figure 6 that looks into wind direction.

Reply: It is true that the validation part of our research has a strong focus on the variable wind speed. However, we do supply a validation for wind direction as well in our manuscript. The results of this validation are summarized in Table 3 of the manuscript, where the mean bias is assessed, next to the match in the wind direction distributions spanning the entire measurement period for each station. In addition, there is also a validation of the wind-direction-dependent wind speed distributions (Fig. S7), which also gives an indication of how well the directional variability is modelled by COSMO-CLM. Nonetheless, an equivalent of Fig. 6 for wind direction is a very interesting suggestion, but since our wind direction validation already covers measurement heights from 62 m to 120 m, the analysis is already implicitly multi-height. A sentence was added to the manuscript at line L340 to highlight this

Because the considered measurements vary substantially in measurement height, i.e. from 62 m MSL up to 120 m MSL, this comparison indicates consistency of the good performance with height.

We have investigated the possibility to clarify the wind direction validation part of the research more, but in the previous round of revisions we already added a subsection in the conclusion which summarizes the model performance in terms of wind direction (L441-L443) as it was asked to expand here more on our validation. Also in the abstract the model's performance for wind direction is briefly mentioned (L6-L8).

Comment 2: Results from figure 8 are somehow counter-intuitive. One would expect that during unstable conditions wakes recover notably faster than during stable conditions. However, we see that this does not happen in the results from TR4 and some parts of TR3. Can authors comment how or why in TR4 the onset velocity close to 0 km is lower for the stable case which then leads to lower velocity deficits (100-150km)? Similarly to TR3, where stable and unstable conditions seem to feature similar wake recovery rate.

Reply: This is a valid and interesting comment, which has also popped up in our discussions. We have done several sensitivity tests to how the transects were computed, but the impacts were always small. The lower onset speed in TR4 is only ∼0.2 m/s and could be influenced by the presence of the wind farm to the south of the southwestern tip of TR4, which is not present in the NOWF simulation (Recall that there is a tolerance angle of 15° around the transect orientation for the inclusion of samples). Similarly, small deviations at the transect tips can be related to farm wake advection / lateral speed-up effects related to the wind farm presence.

It is true that the recovery differences between stability classes are not always according to what is typically found in literature. However, our analysis differs from studies focusing on stability-dependent wake recovery in several aspects. First of all, we look at time-averages of tens to hundreds of samples and not at specific cases. Secondly, the collection of samples in each stability class is a collection of different wind speeds. Thirdly, we consider a very large transect (multi-100km) where the stability criterion and wind direction criteria is evaluated only at the center of each transect so that along-transect variations in wind direction and stability can occur. And finally, we consider wind farms of non-existent sizes, further hampering the

comparison with studies based on present-day wind farms.
Nonetheless, we do clearly see that over the wind farms, the mean wind speed reduction is generally weaker under unstable conditions, which does point to enhanced mixing of momentum under unstable conditions. More so because the wind farm forcing actually leads to the strongest relative wind speed reductions for unstable conditions according to the following reasoning: The term $V * C_t$ in the wind farm parametrization, which determines the relative wind speed reduction (Fitch et al., 2012), is largest for the rated wind speed and the wind speeds under unstable conditions are most similar to the rated wind speed of the three stability classes. According to our quantifications the mean relative reductions should be 5% to 20% stronger for unstable conditions along transects TR1, TR2 and TR4 because of this.
Furthermore, the large wind farms considered in this simulation also add considerable TKE to the boundary layer and in relative terms more so for stable conditions because it is for these sub-rated wind speeds that $Ct - Cp$ is largest. The advection of this large TKE amount behind the wind farm might further enhance the wake recovery under stable conditions. Also, since the stability criterion is computed for the NOWF simulation, this analysis does not consider the modification of the atmospheric boundary layer (incl. stability) due to the wind farm forcing, whereas it is possible that this forcing leads to e.g. strongly enhanced mechanical turbulence also under stable conditions.
To conclude, our stability-based analysis of the wind farm runs show that the annual impacts of the wind farm forcing are substantial for all stability classes, but that unstable conditions show lower deficits over the wind farm and by extension often also lead to smaller reductions at the inflow of the next wind farm. It does not clearly show differences in wake recovery, but there are substantial differences with how this is analyzed in other studies and other research setups would be more suitable to investigate the topic of stability-dependent wake recovery. To address this topic in the manuscript, the following text was added in the results and discussion section, after line L380

However, the transects do not show a significantly slower wind farm wake recovery for stable conditions, as has been found based on observations (Cañadillas et al., 2020; Platis et al., 2021). The presented transect analysis also differs strongly from such studies in that it considers time-averages of different wind speeds and covers a very large extent with the stability and wind direction criterion only evaluated at the center of the transects. Added to that, modifications of dynamic stability by wind farms, which have previously been modelled with LES (Porté-Agel et al., 2014; Lu and Porté-Agel, 2015), could be strongly enhanced by the large, non-existent wind farms used in this study.

Comment 3: Abstract, L11-13: "However, the long-term impact of wake losses in and between wind farms is mitigated by adopting next-generation,15 MW wind turbines instead of 5 MW turbines, as the layout-integrated, annual energy production (AEP) in the simulation increases by over 27% at the same capacity density." I am unsure what you mean by this sentence; I think the readers would, too. Would you reformulate?.

Reply: This was indeed a convoluted way to make clear that choosing 15 MW turbines over 5 MW turbines increased the layout efficiency. The use of the verb "mitigate" was therefore omitted and a more simplistic formulation was chosen. The next sentence has now been moved in front of this sentence to make the structure more logical. The adapted sentence is indicated in bold below

The wind farm simulations indicate that for a typical capacity density and for SW-winds, inter-farm wakes can reduce the capacity factor at the inflow edge of wind farms from 59% to between 54% and 30% depending on the proximity, size and number of the upwind farms. The efficiency losses due to intra- and inter-farm wakes become larger with increasing capacity density as the layout-integrated, annual capacity factor varies between 51.8% and 38.2% over the considered range of 3.5 to 10 MW km^{-2}. ***Also, the simulated efficiency of the wind farm layout is greatly impacted by switching from 5 MW turbines to next-generation, 15 MW turbines, as the annual energy production increases by over 27% at the same capacity density.***

Comment 4: Equation 2. In Latex, PSS results in separated characters that look weird. Please use to fix this. The same applies to CF and other variables with more than one character throughout the manuscript.

Reply: We agree that this way of writing the variables did not fit the text well. Therefore, all mentions of variables were adapted accordingly in the manuscript and the equations. This was done throughout, to ensure consistency. This concerns equations (1)-(6) and the associated variable mentions throughout the text.

Comment 5: In figure 8 caption, indicate it is mean wind speed "deficit".

Reply: We have currently phrased the caption as "Relative deficit of the along-transect mean wind speed". Also in the label for the y-axis of the figure we have repeated this. We have tried to rephrase the caption slightly, but have eventually decided to keep the original formulation as it seemed to us the most readable.