

Answer to Reviewer 1

March 16, 2017

Thank you for reviewing the article. I have copied your comments in bold letters and answered them individually.

I do agree with your conclusion but I would like to have a more extensive discussion on how one can make such a conclusion. In figure 6 you show very interesting results at two positions. I think it would be very interesting to see how the turbulence levels also vary with downstream position. You discuss that there are principal differences on how the farm is modeled and how the flow vary due to this. A plot of how the turbulence change with downstream position would ad a lot of understanding of what goes on. (Figure 4 with TI would be a fast solution)

I have added two plots of turbulence intensity in Figures 1 and 2, which show that the levels of turbulence intensity in the simulation of the roughness change are much lower and smeared out compared to the turbulence intensity observed in the simulation including the 25 ADs. These plots confirm the results shown in Figure 6 of the submitted article. I think it is enough to add Figure 1 to the revised article.

On page 9, about line 7-11, you state that the Coriolis force is indirectly causing the wind farm wake deflect clockwise because the present wind veer. But I do believe you need to discuss how you can make such a conclusion more in depth. You also use the single wake example to verify your conclusion but it is not very clear how that supports your conclusion.

I can add the following (in italic font) to clarify the conclusion:

When the wind farm is represented by 25 ADs (top plots of Figure 6), the turbulence and V -momentum change both near the wall and above the wind turbines. In both the wind farm and the near wind farm wake, the change in turbulence is larger than the combined change of Coriolis force and pressure gradient, especially above the wind farm, where also the imbalance of V -momentum in the near wind farm wake is the largest. *This indicates that the turbulence is mixing flow from above the wind farm, down into the wake region. Since the flow above the wind farm has a relative wind direction towards the right due to the present wind veer, the wind farm is wake is turned clockwise.* In other words, Figure 6 suggests that the Coriolis force is indirectly causing the wind farm wake to deflect clockwise because of the present wind veer, and not because of the local changes in the Coriolis force as motivated in previous work (van der Laan et al., 2015a).

At moment, we have no other arguments that support this conclusion.

The single wake study shows that if the wind veer is strong, it turns even more the wake clockwise. This is an indication why the wind farm wake is also turning clockwise in the neutral case when the wind veer is less strong, but it is not a hard proof.

a minor comment: page 1, line 17, "curved rows" is not very clear.

The deflection of the upstream wind farm wake resulted in a lower power production of the downstream wind farm, because the Coriolis force aligned the upstream wind farm wake towards the curved *wind turbine* rows of the downstream wind farm.

In summary, I agree with the authors and think it is an interesting article that could be modified and accepted with limited effort. However, a deeper discussion on how these conclusions can be made is needed. The result in figure 6 in combination with the large differences in setup with individual turbines (disks) or roughness needs to supported by a discussion arguing that one can rule out other reasons. (Or at least say that they are of smaller order.)

I agree that our approach does not rule out the possibility of a wind farm wake turning the opposite direction in neutral conditions. Very recently, Allaerts and Meyers [1] have reported that a wind farm wake turns slightly counter clockwise (2°) in their large eddy simulations (LES) of a wind farm in neutral atmospheric conditions and argued that the local change in Coriolis force dominates the turbulent transport of spanwise momentum, rather than the wind veer. However, the observed turning is so small that it becomes challenging to extract it from a LES data set. This is because

the (neutral) atmospheric boundary layer that is inserted at the inlet is always developing downstream, which can lead to small wind direction changes in the wind farm. In our RANS simulations, the neutral ABL is in balance with the entire domain. In addition, one might need to simulate a very long time in LES in order to obtain a statistically independent average of a small quantify such as the wind direction deflection in neutral conditions. I think it is a good idea to add this discussion (and reference) in a revised version of the article.

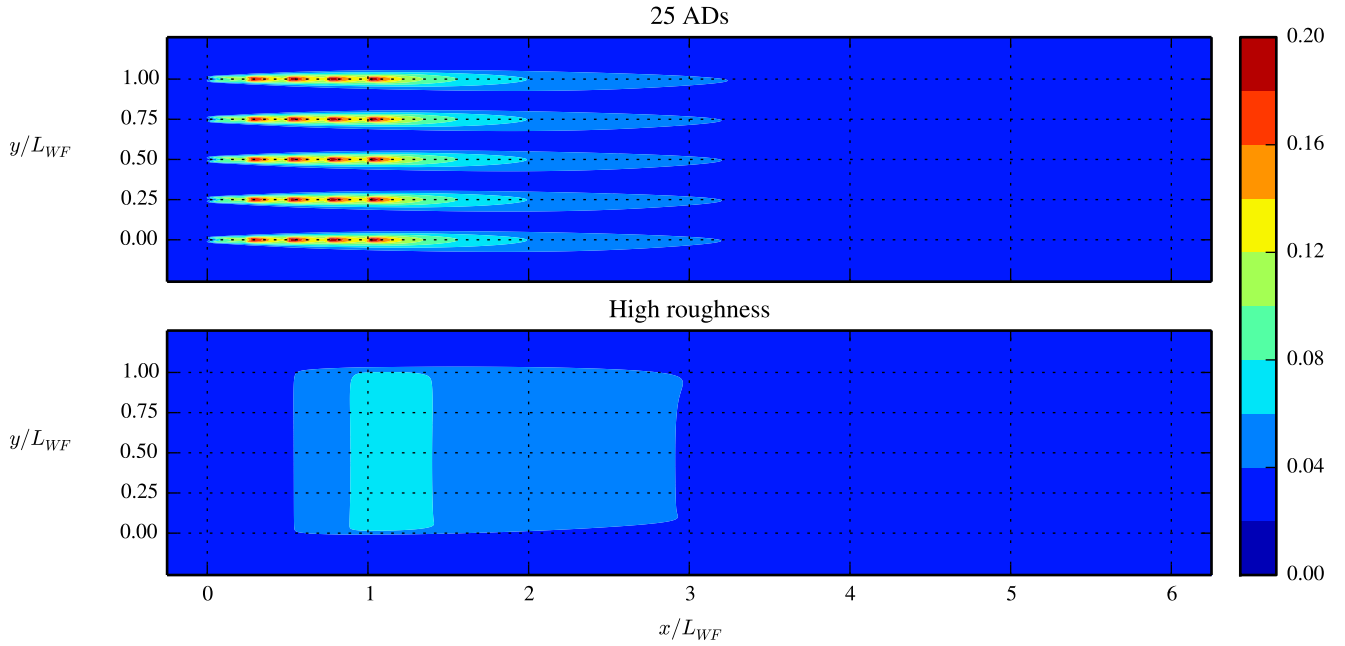


Figure 1: Turbulence intensity at hub height. Top: Wind farm modeled with 25 ADs. Bottom: Wind farm modeled as a high roughness.

References

- [1] Allaerts, D. and Meyers, J. Boundary-layer development and gravity waves in conventionally neutral wind farms. *Journal of Fluid Mechanics*, 814:95–130, 2017.

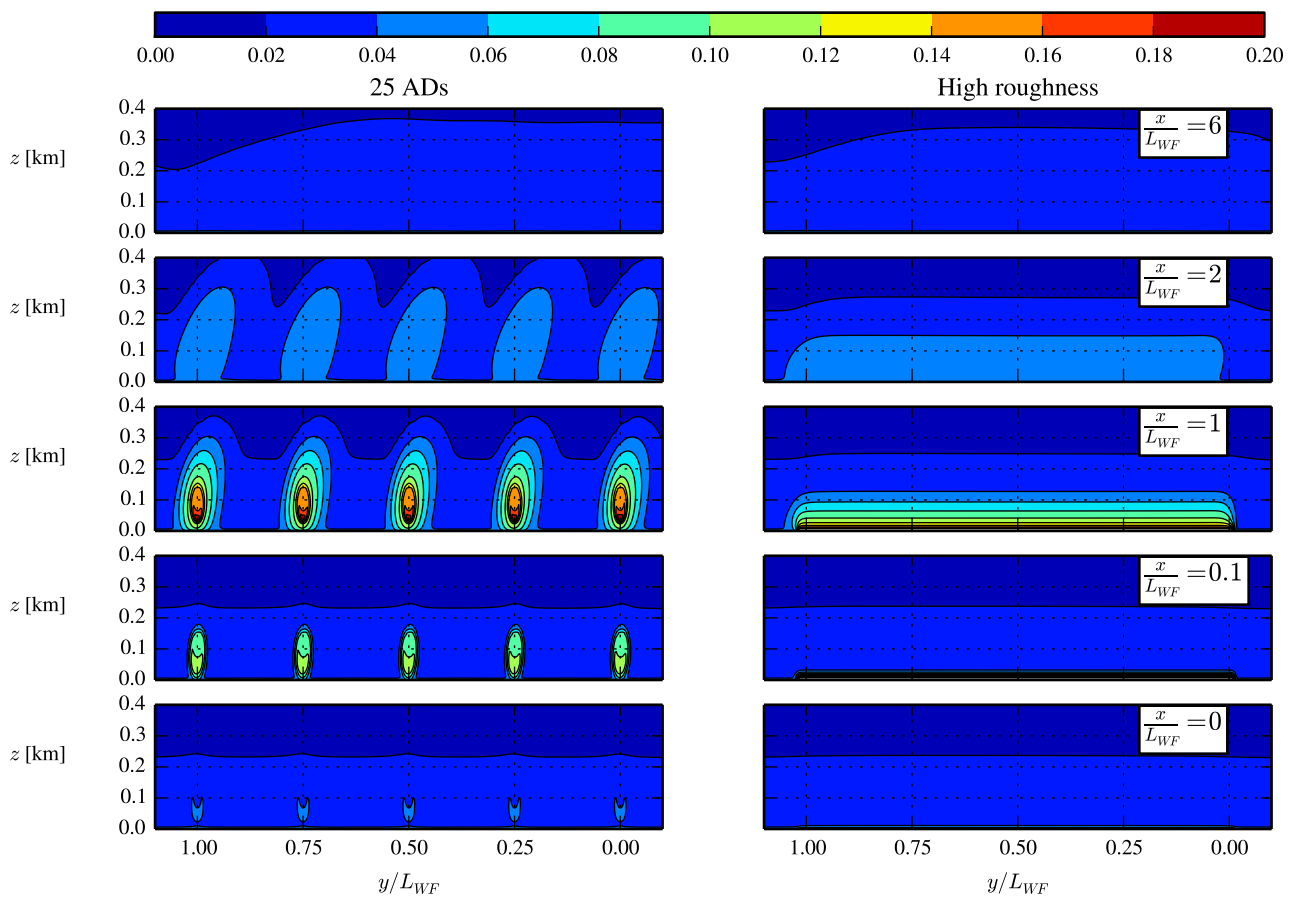


Figure 2: Turbulence intensity at several downstream cross planes. Left: wind farm is represented by 25 ADs. Right: wind farm is represented by a high roughness. Wind farm ends at $x/L_{WF} = 1$.