Comments on the review by Reviewer 2 of "Evaluation of tilt control for wind-turbine arrays in the atmospheric boundary layer"

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I thank Reviewer 2 for his/her comments and suggestions which have helped to improve the manuscript.

During the revision process I became aware that most of the simulations had problems in the roughness lengths values selected by the input files (in particular the roughness lengths of the precursor simulation where different from those of the simulations with the turbines). All the simulations have therefore been repeated with consistent correct values ($z_0 = 0.001$) and the manuscript has been modified accordingly. The main results are not changed, so that the conclusions of the study are not affected by these updated results (but, where appropriate, some quantitative values have been updated in the revised manuscript, as can be seen in the highlighted copy of the manuscript).

Following the referees comments and suggestions, the manuscript has undergone a non-negligible revision, where the main modifications are the following:

- All figures and tables have been updated with the results from the new simulations (with the correct consistent value of z_0). Changes resulting from these new simulations are updated in the revised manuscript.
- Additional simulation have been performed to further analyze power gains that can be obtained with $C'_T < 3$ values. These additional results are presented and discussed in the newly-added Appendix B and are mentioned in the main text when appropriate.
- The need for a detailed structural load analysis is further emphasized in the conclusions.

Each issue raised by a specific comment in the report is addressed in detail below. Modifications of the manuscript can be tracked in the highlighted version of the revised article (red = removed, blue = added or modified).

The author investigates the impact of rotor tilt angles and thrust coefficients on power gains of groups of turbines across varying atmospheric boundary layer heights. Additionally, the influence of rotor diameter is examined on performance gains and streak amplification across the various conditions. The performance gains found are quite significant, although they are only determined for wind-aligned operation. The paper is well written and thorough in its explanation and analyses.

I am glad of this positive general opinion on the manuscript.

1) The author examines a range of positive tilt angles including 20, 30, and 40 degrees, finding across all the conditions that a tilt angle of 30 degrees gives the greatest increase in power production. The author also states that these tilt angles would best be accomplished with downwind rotors/blades. However, a tilt angle of 30 degrees seems *significantly larger than what is currently reasonable with turbine designs. The reviewer feels the reader would benefit from some discussion of the practicality of tilt angles in this range to help ground the results.*

Clearly, it is not possible/practical to implement the type of tilt control analyzed in this study for current-generation wind turbines, especially with the computed optimal tilt angles. However, it might be possible to implement it in future generations of wind turbines if positive tilt-capabilities are required in the design phase. The revised manuscript has been to make this clear in both the introduction (lines 29-34) and the conclusions (lines 280-289).

2) Along the lines of comment 1, including some discussion of the potential impact on turbine loading would be useful to the reader as well.

From a speculative point of view, I do not see critical loading problems in the significant-tilt high-C_T' regime because a significant tilt greatly reduces the u_d wind component normal to the rotor and therefore the thrust force which scales like u_n^2; in this context an increase of C_T' would, probably only partially, compensate the reduction of the thrust force (which scales linearly in C_T'). An issue could come from the blade-bending moment generated by the gravity force which would develop a component normal to the rotor and directed towards the ground when the rotor is tilted; however, the tilt would also induce a vertical component in the aerodynamics forces which is directed in the opposite vertical direction as the generation of the streamwise vortices is due to a positive lift force on the rotor; in this context, increasing C_T' would probably be beneficial to counteract the bending moments induced by gravity forces.

I have refrained from including the above discussion in the manuscript because it would be too speculative and potentially misleading if unsupported by data. The problem is that providing such data, besides being outside the scope of this study, would be problematic. Indeed, I could have run a few simulations using the FAST model in SOWFA which would provide load data for the NREL-5MW turbine but the relevance of these hypothetical results would be questionable because (a) this turbine is the smallest one considered in this study and it has not the optimal size for any of the considered ABLs and (b) the NREL5-MW represents current-generation wind turbines which have not been designed to be tilted by large angles, or even with the required positive tilt angles as they have upwind-facing rotors. It would make much more sense to compute the loading of turbines such as the SUMR-13MW model considered by Bay et al. (Flow Control Leveraging Downwind Rotors for Improved Wind Power Plant Operation, 2019 American Control Conference, Philadelphia, PA, USA, July 10-12, 2019) but I have no access to a FAST model for it that I could use in SOWFA (and creating it would go much beyond the scope of this study) and, probably, even if I had it, it should probably go through an additional design phase to optimize the blades for high-tilt operation.

In the revised manuscript I therefore mention (lines 277-289) that additional studies are needed where structural loads are computed for tilted turbines operated at high C_T', especially for next-generation wind turbines.

3) The flow diagrams in figures 3 and 4 are very useful to the reader in order to visualize the benefits of using positive tilt angles to deflect the wakes and draw higher velocity flows downwards for the downwind turbine. While the reviewer can understand why the author may have only included flow diagrams for once case in order to keep the main body of the paper concise, it could be helpful/interesting to the reader to include flow diagrams of some of the other cases in the appendices. Unless of course the flow is not significantly different, in which the author should then state that in the manuscript.

I appreciate that the reviewer understands the effort put in trying to keep the paper short and readable.

I reproduce a sample of flow diagrams in the three figures below. From Fig. R.2.1, showing the case of the D=180m wind turbines in the three considered ABLs with H=750m, H=500m and H=350m respectively, it is seen that the flows are extremely similar in the three ABLs and very similar to those shown in Fig. 3 of the manuscript. From Figs. R.2.2 and R.2.3, showing the case of the four considered turbine diameters (D=126m, D=180m, D=250m, D=360m) in the H=500m ABL, it is seen that all the flows are similar except for the southerly wind veer effect which begins to become significant for the largest considered value of the ratio D/H=0.72 corresponding to the D=360m turbine in the H=500m ABL. This is now explicitly stated in the revised manuscript (lines 189-192).

For the sake of focus and conciseness of the manuscript I prefer not to reproduce in it, in an additional appendix, these extra fields which do not add much to the discussion (I have already added an appendix presenting additional results at intermediate C_T' values).

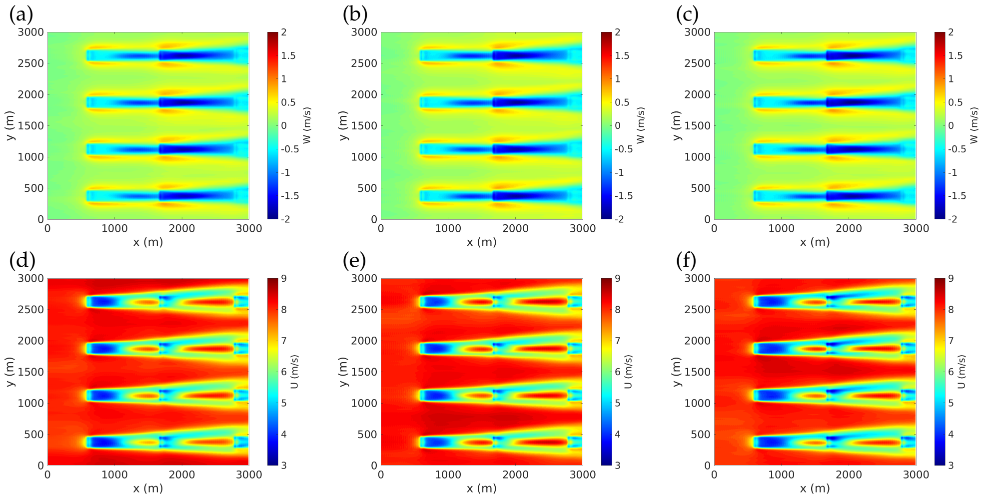

Fig. R1.1 Time-averaged vertical (top row) and streamwise (bottom row) velocity fields in the horizontal plane at hub height for the simulations of the D=180 turbines in the H=750m (panels a and d), H=500m (panels b and e) and H=350m ABLs (panels a and d) with control turbines tilted by $\varphi = 30^o$ and operated at $C_T' = 3$.

4) In the conclusion, the author acknowledges that more work is to be done to determine the gains that would be possible across a typical wind rose. The reviewer believes the paper would be strengthened by including discussion on what the results may look like in a partially waked case, as the high velocity streaks would not be as well aligned with the downwind turbines, and could even cause undesirable loads across the rotor.

This is a very interesting remark. Probably the best fix for a partially-"streaked" case would be to add a bit of yaw control to steer the high-speed streak towards the downwind rotor and keep it "totally streaked". This is now mentioned in the conclusions of the revised manuscript (lines 257-261).

I hope to have clarified the main issues raised in the report. I thank again Reviewer 2 for his/her comments and suggestions which have helped to improve the manuscript.

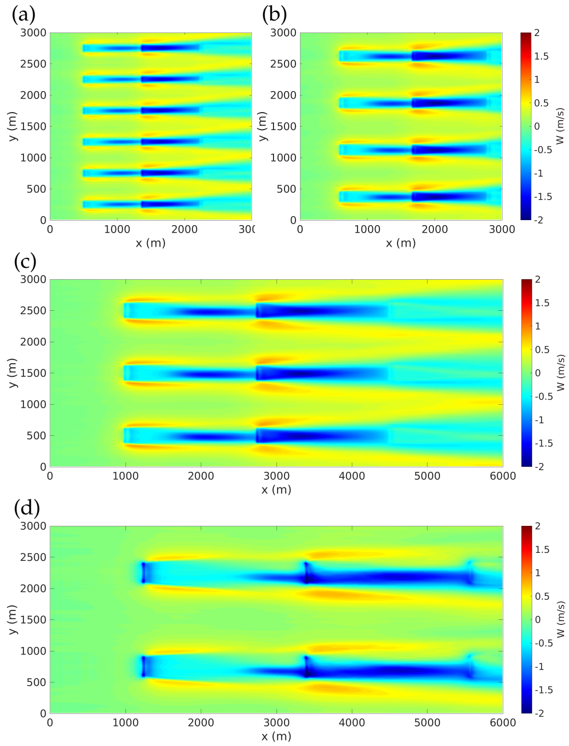

Fig.R2.2 Time-averaged vertical velocity fields in the horizontal plane at hub height for the simulations in the H=500m ABL of the arrays of (a) D=126m, (b) D=180, (c) D=250m, (d) 360m wind turbines with control turbines tilted by $\varphi = 30^o$ and operated at $C_T' = 3$.

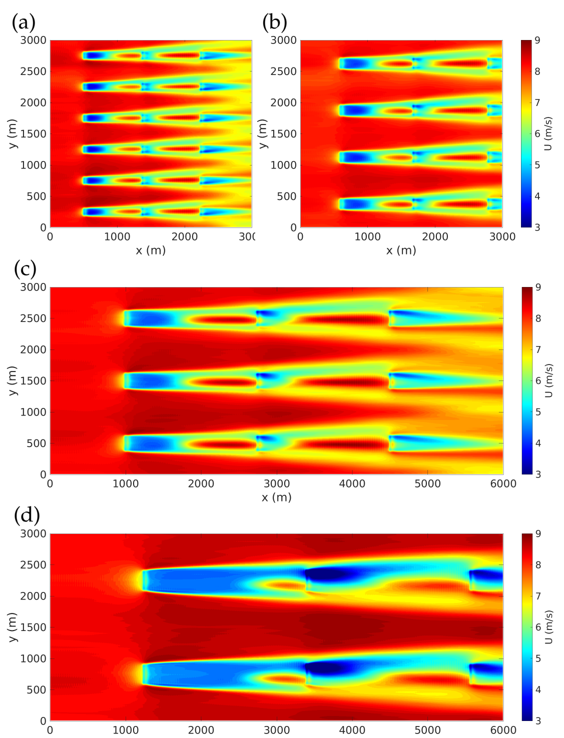

Fig.R2.3 Time-averaged streamwise velocity fields in the horizontal plane at hub height for the simulations in the H=500m ABL of the arrays of (a) D=126m, (b) D=180, (c) D=250m, (d) 360m wind turbines with control turbines tilted by $\varphi = 30^o$ and operated at $C_T' = 3$.