Response to Referee #2

We thank the referee for their review and their thoughtful comments. Point-to-point responses can be found below, and the relevant changes will be made to the manuscript during the revised manuscript submission stage.

Main comments:

Comment #1

Line 50: *Stable ABL low-level jets are generated, in part, by inertial oscillations induced by Coriolis forces (Van de Wiel et al., 2010)*. The mean effect of the low-level jet can be explained in a more simple way see a recent work of the reviewer van der Laan et al. (2021), where it is shown that the Coriolis-induced wind veer causes the jet. Once the wind veer is removed, using the veer-less ABL model, then the jet is neither present. This is the case for analytic solutions, RANS models and LES. (van der Laan et al. (2021) does not include LES results but a colleague has tested the veerless model in an unpublished work using the GABLS test case from Svensson et al. (2011) and neither got a jet.)

Response

Thank you for the comment and for directing us to van der Laan et al. (2021). This is a great paper, and provides useful insight using idealized models.

Modification:

Stable ABL low-level jets are generated, in part, by Coriolis-induced wind veer (van der Laan et al. (2021)) and by inertial oscillations induced by Coriolis forces (Van de Wiel et al., 2010).

Comment #2

Figure 2: What is the spacing between the wind turbines? You should mention this important parameter in the text or you could plot the layout normalized by the rotor diameter and use grid line in the plot. It looks like the chosen spacing between the wind turbines in y is relatively small (4D?), which enhances the benefits of wake steering. I think you should note that you are investigating a relative small spacing and that your energy gains due to wake steering are expected to be less for large wind turbine spacing. Why didn't you use a more realistic wind farm layout representing a modern wind farm? In other words, how would your main conclusions on yaw control methods change for different wind farm layouts?

Response

Thanks for highlighting this important point. We have added the spacing to Figure 1. The referee is correct that the gains from wake steering are specific to the wind farm geometric setup among other details of the simulation, including but not limited to the turbulence in the ABL, the surface heat flux boundary condition, the geostrophic wind speed and direction, and the shear/veer. We selected the layout of the farm to be a representative, idealized test case for wind farm control similar to previous wind farm control studies [1] and with spacing comparable to wind field sites of interest from our research [2]. We have added further discussion to highlight that the gains from wind farm control will be case specific.

Comment #3

Wind direction and stability: Do I understand correctly that you are both investigating the effect of stability and wind direction at the same time and that stable and unstable conditions reflect South-Western and Western wind directions, respectively? If yes, then it is not fair to compare stable with unstable directly (as you do in the paper in lines 340-342, Table 1 and elsewhere) because they represent different wind direction flow cases. If you want to compare stable with unstable, you should have the same wind direction or you could perform multiple wind directions for both stable and unstable such that your model results represent the same wind rose. If the latter is not desired by authors then you should at least rename and clarify the cases (to for example something like stable-SW and unstable-W or stable-diagonal and unstable-row). If the wind direction is the main parameter of interest for the yaw control optimization studies, then you could have used a quasi-steady stable and unstable ABL using a geostrophic wind direction that varies over time (in order to get the same wind direction cases).

Response

The primary purpose of the paper is to test the closed-loop wake steering methodology proposed in Part 1 (Howland *et al., Wind Energy Science*, 2020, 5, 1315-1338) in an idealized ABL case with inflow wind condition variations as a function of time. In Part 1, we develop a closed-loop wake steering methodology and test its performance in the statistically quasi-stationary CNBL. Here, we are interested in comparing the performance of the closed-loop control to existing open-loop control methodologies in an example transient ABL case. We select the diurnal cycle case to exhibit both wind direction and stability variations, which both have substantial impact on wake steering control.

The referee is correct that the present simulation does not contain controlled experiments between stable and unstable cases since the wind direction has changed. We have clarified this further in the manuscript. It is worth noting that the wind turbine spacing is larger for the stable-SW condition than for the unstable-W condition. Given the turbine spacing and also the multiple wake interactions superposed, for fixed stability, the flow from the west would likely result in larger wake losses and likely more potential for wake steering. However, the effect of stability outweighs the farm geometry in this particular simulation.

We have added more discussion of this point to the paper and modified Table 1 to note the wind direction.

Comment #4

Section 4.1 and Figure 6: Do I understand correctly that you derive a power-yaw relationship for the two leading wind turbines using the LES results where all wind turbines are active? This can lead to different results compared a wind turbine in isolation, which is normally used to estimate a power-yaw relationship. I think you should mention this in the article.

Response

We agree that this could lead to different results compared to a wind turbine in isolation. We have added further discussion to the manuscript on this point.

Comment #5

Appendix C: Note on wake steering LES initialization: You mention that you cannot get the same result by running the same LES on a different number of CPUs. First of all, I appreciate the fact that you also report the model challenges. I agree that the chaotic nature of the real atmospheric makes it impossible to measure the same ABL twice. However, for idealized CFD simulations of the ABL, one should be able to get the same result regardless of the number of CPUs, as long as the number of CPUs does not affect the number of cells in the numerical grid, the use of random number generators is avoided (or used with a fixed seed) and the communication between CPUs is handled in a consistent manner. The LES model of the in-house CFD (finite volume) code of DTU Wind Energy (EllipSys3D) does currently not have the parallelization issue. However, we have noticed that round off issues due to inconsistent communication between CPU's previously led to a different times at which the turbulence started to form (which has been fixed). The authors are welcome to contact the reviewer (after the review process) for further discussion.

Response
Our in-house LES code *PadeOps* (https://github.com/FPAL-Stanford-University/PadeOps) is pseudo-spectral (spectral methods in horizontal, 6th order finite difference in vertical direction). As the referee has noted, small differences in two solutions at round-off magnitude grow exponentially in time due to the instability of the chaotic Navier-Stokes system (Lyapunov stability). In our experience with wall-bounded turbulence, round off errors of the order 1E-13 generate order 1 deviations in local skin frictions in about 250-500 RK4 time steps.

There are several aspects of the discretization algorithm that introduce these round-off level perturbations. The spectral discretization requires Fourier transforms that are very aggressively optimized for the specific decompositions (for example the reviewer is referred to the “exhaustive” plans available as part of the FFTW library for complex Fourrier transforms to identify efficient algorithms in routines such as “fftw_plan_many_dft”). This aggressive optimization ensures that the most optimal FFT algorithm is identified and used for each specific individual simulation. This is the primary source of round-off perturbations at double-precision level determined by the compiler type, optimization flags and distributed memory partitioning topology.

As discussed in Appendix D, round-off error is introduced by changing this parallel processor topology. While these round-off errors grow to order 1 deviations in instantaneous snapshots, it is not expected that they would alter mean flow statistics (averaged over long periods). However, in the control simulations presented, which use Fourier collocation, the wake steering controller interacts in a nonlinear fashion with finite time-averaged statistics, and differences in the finite time-averaged power production statistics appear (shown in Appendix D). When we fix the parallel processor topology, round-off error is eliminated in *PadeOps* (Appendix D). We would also be happy to discuss the DTU code’s methodology in the future to hear about the solution methods which have been implemented.

Point comments:

Comment #1
Section 3: You could adde that you use a barotropic atmosphere since you use a constant geostrophic wind speed.
Response
We have added that we consider a barotropic atmosphere with no geostrophic wind shear from baroclinicity.

Comment #2
Figure 5, caption: Hub height velocity should be hub height wind speed (or stream-wise velocity?).
Response
We have clarified this in the manuscript.

References

[1] Doekemeijer, Bart M., Daan van der Hoek, and Jan-Willem van Wingerden. "Closed-loop model-based wind farm control using FLORIS under time-varying inflow conditions." *Renewable Energy* 156 (2020): 719-730.

[2] Michael F. Howland, "Wind farm yaw control set-point optimization under model parameter uncertainty", Journal of Renewable and Sustainable Energy 13, 043303 (2021) https://doi.org/10.1063/5.0051071