Response to Associate Editor comments: Wake steering under inflow wind direction uncertainty: an LES study

Thank you for the additional comments. This documents contains responses to each question and links to relevant changes in the manuscript.

1. Reviewer 2 raises two related concerns regarding the role of atmospheric stability and inflow stratification in determining wake recovery and the effectiveness of wake steering. In your response you indicate that this limitation has been acknowledged in Section 4.2, but the revised manuscript does not explicitly discuss atmospheric stability, and the current wording focuses primarily on the diurnal cycle. These are not equivalent, and the discussion should more clearly address stability as a governing physical factor.
Please revise the manuscript to explicitly acknowledge that atmospheric stability and inflow stratification strongly influence turbulence intensity, shear, and wake recovery, and therefore can substantially modify both wake dynamics and the effectiveness of wake steering strategies. Because the simulations in this study employ a conventionally neutral boundary layer inflow with relatively low turbulence intensity and mild veer, the results represent a limited subset of atmospheric conditions that are generally favorable for wake steering. The manuscript should therefore clearly state that the conclusions may not directly extend to more strongly stable or convective boundary layers, where wake recovery rates and wake steering performance may differ substantially. Adding a short paragraph explicitly framing this limitation and clarifying how the chosen inflow conditions relate to the broader range of atmospheric stability regimes encountered in real wind farms would more completely address this concern.

Yes, we agree that the atmospheric stability is a key determinant of wake behaviour and wind farm flows, and certainly will change the effectiveness of wake steering. A main discussion point in the Introduction (lines 27 - 43) is that wake steering is highly dependent on the ambient conditions - particularly TI - of which atmospheric stability is a main driver. As mentioned in Section 2.3, lines 157 - 160, we specifically chose a CNBL with a low TI and below-rated velocity in order to investigate the impact of uncertainty and bias in inflow wind direction in favourable conditions. This means that the fact that we see significant sensitivity to these factors, even for this flow case, in our opinion strengthens our conclusion that this is a significant potential issue for applying wake steering operationally, and motivates the improvement of measurement technologies and the inclusion of uncertainties in low-fidelity models. We do recognise that it is important to more deeply discuss the impact of our choice of ABL stability on the results, and hence we have expanded our Discussion section to include further details regarding the atmospheric stability aspects.

The first place this is addressed is related to the use of the Gaussian convolution to estimate the impact of higher wind direction uncertainties, the first part of the comment by Reviewer 2. Section 4.2, lines 463 - 468 now read as follows (green = text added in new version):

'Perhaps the biggest limitation of the results is applying a Gaussian convolution across a range of

wind directions in order to extrapolate the impact of wind direction uncertainty. This relates firstly to atmospheric stability: in reality, a higher measured wind direction uncertainty may be indicative of more unstable conditions and higher turbulence intensity. This would therefore lead to improved baseline wake recovery, and hence may make wake steering unfavourable regardless. However, the maximum chosen value of $\sigma_{WD} = 4.5°$ *is representative of measured values during wake steering experiments, hence is likely to be reasonable as a upper bound to consider (Simley et al., 2020, 2021).'*

Secondly, to more specifically address the fact that the wind farm flow and performance would be different depending on the stability condition, and our motivation for the use of a favourable condition for wake steering, we have added the following, also in Section 4.2, in lines 479 - 487:

'Other possible limitations inevitably stem from the single wind farm configuration and ABL inflow that are utilised. As LES is computationally expensive, care was taken in the study design to create a fair and reasonable setup, that allowed the impact of wind direction uncertainty to be investigated in a flow scenario where wake steering was likely to be beneficial. Therefore, the fact that high sensitivity to wind direction is shown even in this favourable flow scenario further highlights the need to improve both models and measurements, and the caution required when applying yaw control to real wind farms. Atmospheric stability is a key determinant of wake behaviour, due to driving the ambient turbulence intensity, shear and veer. Therefore, different stability conditions would result in different wake recovery and wind farm performance to that seen here, and hence could result in a narrowing of the range of mean wind directions where wake steering is beneficial, or mean that wake steering is not beneficial at all.'

Additionally, in order to highlight that these are conclusions in a favourable flow scenario, and to generally sharpen the text, the following has been added to the abstract:

'Considering mean wind farm power output, the inflow wind direction standard deviation in the current study ($\sigma_{WD} = 2.3°$*) results in a beneficial window for wake steering of* $8.5°$ *(*$\in [-1.5, 7.0]°$*) with peak total power gains of 23% and 7.5% for the two yaw strategies, respectively. Therefore, an error in assumed or measured mean inflow wind direction of* $\sim 4°$ *could turn a promising prediction into an actual power loss. Extrapolating to an uncertainty of* $\sigma_{WD} = 4.5°$ *using a Gaussian convolution reduces the beneficial ranges to* $8°$ *and* $6.5°$ *respectively, with peak gains reduced to 7.5% and 2%. While exact numbers depend on turbine spacing, the substantial decrease in peak power and narrow range of power gains signify that wake steering is highly sensitive to wind direction uncertainty and small biases in mean inflow wind direction, even in favourable atmospheric conditions. Therefore, accurate measurement of these quantities and inclusion of them in prediction models is essential to the operational implementation of wake steering.'*

2. Reviewer 2 also raised an important question regarding the use of an actuator disk representation rather than an actuator line model. While your response to the reviewer provides a clear and well-reasoned explanation, including a helpful supporting figure, this discussion currently appears only in the response-to-reviewers document and not in the manuscript itself.
Because the choice of turbine representation can influence near-wake structure and therefore potentially affect wake steering predictions, I recommend incorporating a brief version of this explanation directly into the manuscript. In particular, the manuscript should explicitly acknowledge the implications of using an actuator disk model, explain why this approach is appropriate for the objectives and scales considered in this study, and clarify any expected limitations relative to actuator line approaches.
A concise paragraph in the methods section summarizing the key points you made in

the response would strengthen the manuscript and ensure that readers who do not see the review correspondence can understand and evaluate this modeling choice.

We have now expanded Section 2.2 to further elaborate on the specific formulation of the aeroelastic-coupled AD model used here, the close alignment in loading and wakes with the actuator line that we have observed in other works, and mentioning the main limitation (that a shear layer, rather than tip vortices, is shed from the rotor disc). As well as adding a reference to the tip correction used in the AD on line 119, the changes to Section 2.2 are as follows, in lines 122 - 133 (green = text added in new version):

'These AD body forces are applied to the computational grid in three overlapping 240° sections, in which the forcing decreases linearly from a maximum at the blade location to zero at the neighbouring blades. A 1-dimensional Gaussian smearing is also applied in the streamwise direction. This aeroelastic-coupled AD formulation, built from three overlapping sectors each representing a single blade, therefore resembles an azimuthally smeared actuator line or actuator sector. Hence, it is different from conventional AD approaches which often use uniform loading or a rotor-element approach based on aerofoil data (Wu and Porté-Agel, 2011). The AD used here has been validated against the aeroelastic-coupled actuator line model (Hodgson et al., 2021), and other LES codes (Hodgson et al., 2023b), and results in very close alignment with the actuator line in terms of blade loading and thrust coefficient C_T. Therefore, the near wake breakdown and wake development is also well represented, despite the fact that the AD results in a shear layer, rather than tip vortices, being shed from the rotor disc (Hodgson, 2023). It allows non-uniform loading (e.g. due to shear and/ or yaw) and its impact on both turbine response and wake to be captured. The two-way nature of the coupling means that the interaction between loading, deflections and flow is also represented (Hodgson et al., 2021).'

3. Additionally, please clarify the application of the log-law in both the precursor and turbine-resolving simulations in Section 2.3, as requested by Reviewer 2. If this point raised a question for one reader, it is likely that other readers may have the same question. Providing a brief clarification in the manuscript will help ensure that the modeling approach is clearly understood by the broader readership.

In order to clarify the use of the log law for the precursor simulations in Section 2.3, the following has been added in lines 143 - 145 (green = text added in new version):

'Rayleigh damping is applied above a height of 2000 *m (Kemp and Lilly, 1978). At the ground, the log law is applied to the velocity field at the lowest vertical cell centres to calculate the instantaneous shear stress. The precursor is initialised with the following conditions: ...'*

In order to clarify this again related to the successor simulations containing the turbines, the following has been added to Section 2.4, lines 163 - 165:

'All successor simulations utilise the same computational domain, which has dimensions of $13490 \times 4970 \times 3000$ *m* $(47.5D \times 17.5D \times 10.5D)$*. Following the precursor setup, Rayleigh damping is applied above* 2000 *m height, log law is used to calculate the instantaneous shear stress at the lowest vertical cell centres, and the two lateral domain boundaries are modelled as periodic. The refined region extends from the inlet... '*

Finally, you may consider changing the color tables that you use for Figures 2-5 per the guidance at https://publications.copernicus.org/for_authors/manuscript_preparation.html #figurestables, since those figures could not be understood by readers with some types

of colorblindness according to https://www.color-blindness.com/coblis-color-blindness-simulator/

Upon this advice we have changed the colour maps of the flow contour plot figures (2-4) to one which has a light-dark gradient as well as a colour gradient to improve readability for those with colour-blindness, and checked it against the colour-blindness simulator shared.