We thank the reviewer for reviewing our manuscript and providing comments to improve our work. Below are the point-by-point comments, replies and changes.

Specific Comments

(1) I do not believe that the AGWs shown in Fig. 2 are due to topography, but I also believe that the generation mechanism for the simulated AGWs is not relevant to the work. Unless the authors can provide compelling evidence that the AGWs are terrain-induced, any references stating that the AGWs are a result of topography should be removed or reworded. This starts with the first sentence of the abstract. The authors could state that there are a number of generation mechanisms for AGWs (which is why this is a relevant paper, because they can happen for so many different reasons). Lines 244-245 in the conclusion even briefly discuss how there are other trigger mechanisms.

In the second sentence of the abstract, the authors refer to AGWs due to topography as transient phenomena; however, mountain waves are typically stationary, which is mentioned in line 63. I do not believe that the second part of the sentence that begins on line 63 to be correct (unless a citation can be provided). Mountain waves are stationary and can be broken down by the Froude number (Stull, 2017). The characteristics of mountain waves depend on the mean flow and mountain characteristics and as a result are just stretched or compressed but do not advect.

All of this is just to say that for the manuscript, the generation mechanism is not important but that the authors should exercise caution in their justification/discussion of their simulated AGWs.

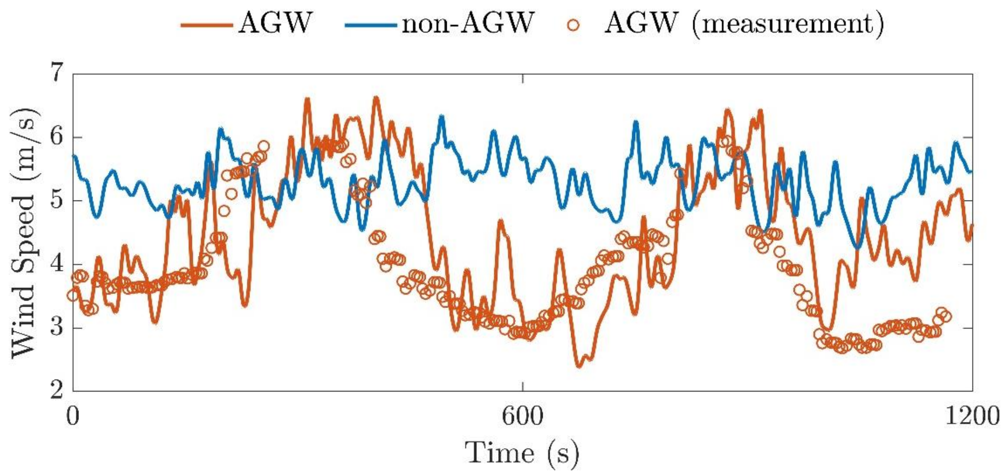
Reference: Stull, R., 2017: "Practical Meteorology: An Algebra-based Survey of Atmospheric Science" -version 1.02b. Univ. of British Columbia:

https://geo.libretexts.org/Bookshelves/Meteorology_and_Climate_Science/Practical_Meteorology_(Stull)/17%3A_Regional_Winds/17.7%3A_Mountain_Waves

Reply

We thank the reviewer for these constructive comments regarding the generation mechanisms and wave characteristics of the present AGW event. Regarding generation mechanisms, we agree with the reviewer that AGWs can be triggered by various atmospheric phenomena, including frontal systems, thunderstorms, and orographic effects. Regarding wave characteristics, we partially agree with the reviewer that mountain waves are stationary in theory. We however would like to note that, mountain waves can also advect, as observed in the work of Sato et al. [1]. Because the precise type of the present AGW event cannot be confidently identified, we have removed the relevant statements in the revised manuscript to avoid over-speculation.

Although we do not ascertain the exact source of this AGW event, we emphasize that our atmospheric simulation, which is constructed by assimilating lidar measurements into LES model, captures the wind speed characteristics associated with AGWs. In Fig. 3 (renumbered as Fig. 2 in the revised draft), the time-height history of wind speed of AGWs from simulation shows overall agreement with measurement. To further quantify this comparison, we have added R-Fig. 1 (Fig. 3 in the revised draft) presenting the time series of wind speed at hub height. The results demonstrate that our simulation not only reproduces the large-scale oscillations observed in the lidar measurement data, but also resolves smaller-scale turbulence fluctuations. Such detailed turbulence information can provide a reliable inflow condition for turbine simulations.



R-Fig. 1: Time series of wind speed at hub-height from simulation for both cases, AGW and non-AGW, and measurement for the AGW case, AGW (measurement).

We would also like to emphasize that the present study is intended as a case study focusing on a specific AGW event. As the reviewer suggested, more accurate characterization of different AGW types is indeed essential for a comprehensive understanding of AGW-wind farm interactions. In future work, we plan to extend our study to other AGW types to further generalize our findings.

Rivision

(i) We have added a description about AGW generation mechanisms in lines 17-18 in Introduction section.

'Atmospheric gravity waves (AGWs) commonly occur when the atmosphere is vertically displaced by topographical features, such as mountains and coastlines, or meteorological phenomena, such as fronts and thunderstorms (Stull, 1988; nappo, 2012).'

(ii) We have added some text concerning different sources of AGWs and the necessity for future studies of these in lines 262-264 in Conclusions section.

'The present work is intended as a case-study focusing on a specific AGW event. Future study should incorporate AGW events originating from various sources and with different wavelengths to comprehensively understand their roles in turbine wake and wind farm flows.'

(iii) We have added R-Fig. 1 as Fig. 3 and added lines 100-102 to clarify imulation-measurement agreement.

'To further quantify these comparisons, we show in Fig.3 wind speed time series at the hub-height. The results indicate that our simulation not only captures the large-scale wavy oscillations observed in the measurements, but also resolves smaller-scale turbulent fluctuations.'

(2) The authors simulate a conventionally neutral boundary layer; however, the decision to use a CNBL needs to be justified. During the period in which the lidar data is extracted, I assume that some information about stability could be extracted from other instruments at AWAKEN. How AGWs affect wake characteristics could vary significantly in stable or unstable conditions and this should be discussed.

Reply

We agree with the reviewer that thermal stability can significantly affect wake characteristics. In our simulation, we assimilated the AGW wind speed profile from the AWAKEN measurements, while the temperature profile was simplified as a CNBL. This simplification was necessary because temperature measurement data were not available for the present AGW event. Consequently, the atmospheric condition in our simulation is neutral, whereas in reality it could have been either neutral or thermally stable. We acknowledge this limitation and will address the simulation of AGWs under non-neutral thermal stratification in our future work.

Despite the absence of temperature measurements, our approach still captures the turbulence characteristics of AGWs and thus provides a reliable inflow condition for turbine simulations, as also discussed in our response to Specific Comment (1). Moreover, the observed increase in turbulence levels under AGW conditions is consistent with the findings of Wise et al. [2], who simulated another AGW event from AWAKEN using a WRF-LES model with both velocity and temperature data.

Rivision

We have added clarification on stability effects in lines 80-82.

'Such a simplification of thermal stability condition is necessary due to lack of temperature measurement data. Consequently, the atmospheric condition in our simulation is neutral, whereas in reality it could have been either neutral or

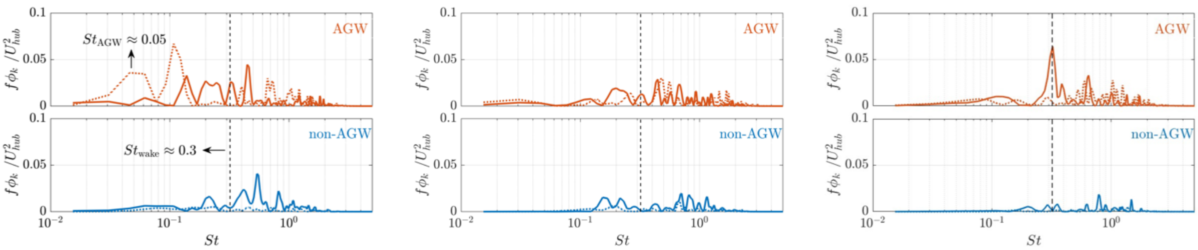
thermally stable.'

(3) At the end of Section 3.1, the authors state that the presence of AGWs increases both horizontal and vertical meandering. Why they increase vertical meandering is relatively intuitive; however, the manuscript does not provide any discussion or analysis on why they increase horizontal meandering.

Additionally, Figure 4 is a nice visualization, but it would be nice to be helpful to see the large-scale AGWs in the flow. The AGWs shown in Fig. 2 span for 10s of kilometers in the lateral dimension, but Fig. 4 only shows ~250m in the lateral dimension. It would be nice for a reader to qualitatively compare the simulated and observed flow.

Reply:

Similarly to Fig. 8, R-Fig. 2 shows the wake (solid lines) and inflow (dotted lines) spectra for three components of velocity fluctuations (left: streamwise u', middle: spanwise v', right: vertical w').



R-Fig. 2: Wake (solid lines) and inflow (dotted lines) spectra for streamwise fluctuations u' (left), spanwise fluctuations v', (middle), vertical fluctuations w' (right).

For St < 0.3, all three components exhibit higher turbulent kinetic energy in the AGW case (red) compared with the non-AGW case (blue). These fluctuations include not only the low-frequency oscillation at St ≈ 0.05 (clearly observed in w'), but also relatively smaller-scale turbulence structures at $0.05 <$ St < 0.3 (as notably in v' and w'). Previous studies have shown that v' and w' at St < 0.3 directly drive wake meandering [3,4]. Therefore, we infer that the presence of AGWs enhances both horizontal and vertical wake meandering. This finding is consistent with Wise et al. [2], who reported that AGWs can increase overall turbulence levels and amplify horizontal wake meandering.

We also agree with the reviewer that extending the spanwise range of the wake contour in our simulation would enable a more quantitative comparison with radar measurements. However, the spanwise domain size in our current simulation is limited to 3 km, whereas the radar observations in Fig. 2 show AGWs extending over a spanwise scale of approximately 10 km. We adopted a smaller domain because the primary objective of our study is to investigate turbine wake dynamics under local turbulence inflow conditions (on spatial scales of ~100 m) in the presence of AGWs, rather than to resolve the large-scale evolution of the entire AGW system.

Rivision

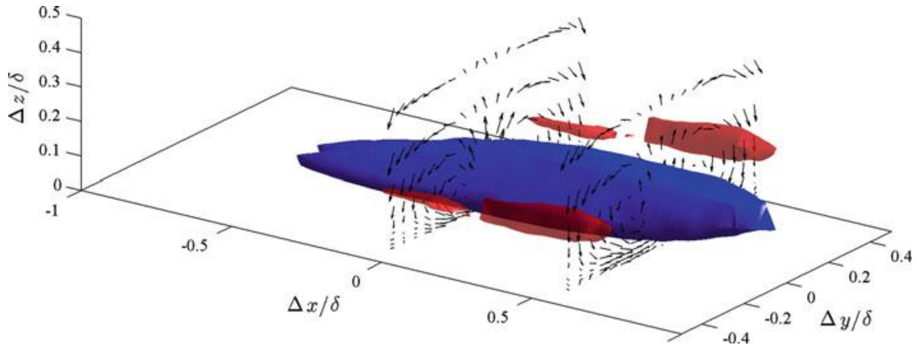
We have added clarification on horizontal meandering in lines 151-155.

'The stronger wake meandering observed in the AGW case can be attributed to the higher TKE at relatively low frequencies, $St < 0.3$. Previous studies have shown that spanwise and vertical velocity fluctuations at such a frequency range directly drive wake meandering (Larsen et al., 2008; Feng et al., 2022). This finding is consistent with the work of Wise et al. (2024), which reported that AGWs can increase overall turbulence levels and amplify horizontal wake meandering.'

(4) In Fig. 8, the higher frequency peak at 0.1 corresponding to the Strouhal number of the atmosphere requires more discussion. Why is there a peak corresponding to the boundary layer thickness? Is this something that is observed or has been seen in other simulations that the authors can reference?

Reply

For wall-bounded flows at high Reynolds numbers, Smits et al. [5] reported that the pre-multiplied TKE spectra in the logarithmic and outer regions exhibit a large-wavelength/low-frequency peak associated with the boundary-layer thickness (i.e., the inversion-layer height in the atmospheric boundary layer). This peak arises from the presence of large-scale, streamwise-elongated structures, as shown in R-Fig. 3. Their characteristic length scale is of the order of the boundary-layer thickness [6].



R-Fig. 3: Large-scale streamwise-elongated structures in wall turbulence [6].

In the present study, large-scale motions in the atmospheric flow are bounded by the inversion layer, which is indicated by the yellow arrow in Measurement (AGW) in Fig. 3 (renumbered as Fig. 2 in the revised draft). Accordingly, a low-frequency peak at St ≈ 0.1 is observed, corresponding to an inversion layer height of approximately 1.25 km.

Revison

We have added an explanation concerning the frequency peak corresponding to the inversion layer in lines 184-189.

'For wall-bounded flows at high Reynolds numbers (e.g. atmospheric boundary layers), Smits et al. (2011) reported that the pre-multiplied TKE spectra in the logarithmic and outer regions exhibit a large-wavelength/low-frequency peak associated with the boundary-layer thickness (i.e., the inversion-layer height in the atmospheric boundary layer). This peak arises from the presence of large-scale, streamwise-elongated structures with characteristic length scales in the order of the boundary-layer thickness (Hutchins et al., 2012).'

(5) In Section 3.4, why are the turbines only separated by only 4D? This seems to be quite a small separation distance. In Fig. 2, the propagation direction of the AGWs is to the northeast and the separation distances look quite large for the wind farms for that wind direction. The only time 4D would be appropriate would be for a due east or due west AGW propagation direction. Ultimately, the findings in this subsection are quite insightful and I feel like it would be very helpful to see a similar setup but with further separation distances.

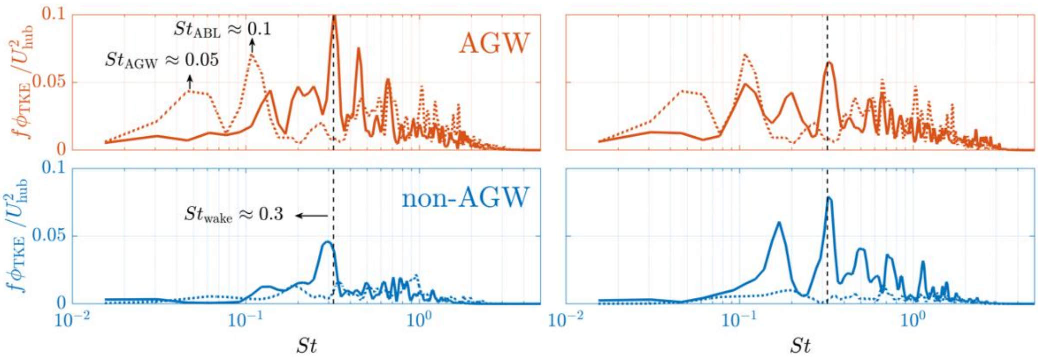
Also, considering that attenuation is discussed in this section, more plots of spectra are needed. It would be nice to see the TKE spectra for the inflow representing downwind turbines or even for just the power signal. Then the attenuation can be quantified.

Reply

The reviewer is correct that the turbine spacing of 4D in our three-turbine simulation is smaller than the spacings typically used in the AWAKEN wind farms. We intentionally adopted 4D spacing to ensure that the downstream turbines remain within the wake region of the upstream turbines, so that their power fluctuations can serve as indicators of upstream wake characteristics.

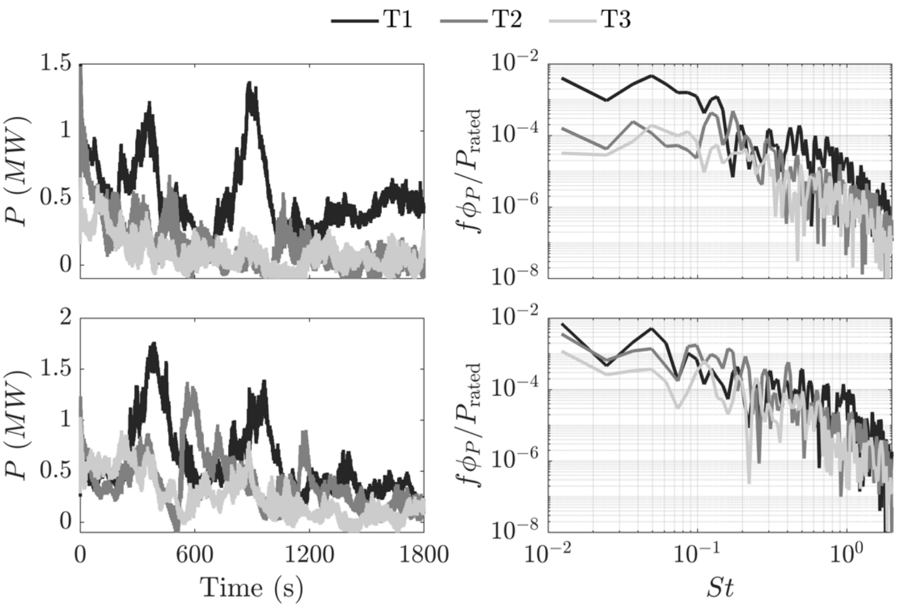
As suggested by the reviewer, we have performed an additional three-turbine simulation with 8D spacing. We also add spectra of power in Fig. 13, together with the power time series. For clarity, here we show (i) TKE spectra from the single-turbine simulation in R-Fig. 4 and (ii) time series and spectra of turbine power from the three-turbine simulations in R-Fig. 5.

R-Fig. 4 shows TKE spectra for inflow region (dotted lines) and downstream 4D (left) and 8D (right) wake region (solid lines) from the single-turbine simulation. In both AGW and non-AGW cases, the wake spectra exhibit a dominant peak at $\mathrm{St} \approx 0.3$. Such a frequency peak arises from a convective shear-instability mechanism that dominates far-wake dynamics, which generates turbulent kinetic energy at $0.1 < \mathrm{St} < 1$. In the AGW case, inflow turbulent kinetic energy at low-frequencies peaks, $\mathrm{St} \approx 0.05$ and $\mathrm{St} \approx 0.1$, shifts to a higher-frequency peak, $\mathrm{St} \approx 0.3$, in 4D downstream. This peak becomes less pronounced in 8D downstream, because wake recovery weakens shear instabilities.



R-Fig. 4: Wake (solid lines) and inflow (dashed lines) spectra at downstream 4D (left) and 8D (right) from the single-turbine simulation.

R-Fig. 5 shows the time series (left) and spectra (right) of turbine power for the three-turbine simulations with 4D (top) and 8D (bottom) spacings. For 4D spacing, the presence of AGWs induces large-scale power oscillations at the first turbine (T1), which are strongly attenuated at the downstream turbines (T2 and T3). For 8D spacing, the attenuation of power oscillations is weaker, and T2 still exhibits visible peaks with a time delay relative to T1. The difference in power attenuation between 4D and 8D spacing is also evident in the corresponding spectra. This behavior is because, as we discussed in R-Fig. 4, the shear instability mechanism that damps low-frequency velocity fluctuations becomes weaker at further downstream.



R-Fig. 5: Time series (left) and spectra (right) of turbine power for the three-turbine simulations with 4D (top) and 8D (bottom) spacings during the AGW event.

From these comparisons, we conclude that a 4D turbine spacing is appropriate for ensuring that downstream turbines are located within the wake region of upstream turbines, thereby highlighting wake-turbine interactions.

Revison

(i) We have added 8D wake spectra for the single-turbine simulation in Fig. 8 (as also shown in R-Fig. 4) and discussed the downstream evolution of wake spectra in lines 194-195.

'For both the AGW and non-AGW cases, such a frequency peak becomes less prominent in 8D downstream, because wake recovery has largely weakened shear instabilities at this region.'

(ii) We have added the power curves for the three-turbine simulation with 8D spacing in Fig. 11 (as also shown in R-Fig. 5) and discussed the power attenuation in lines 230-235.

'Figure 11 shows time series (left) and spectra (right) of turbine power for the three-turbine simulations with 4D (top) and 8D (bottom) spacings. For 4D spacing, the presence of AGWs induces large-scale power oscillations at the first turbine (T1), which are strongly attenuated at the downstream turbines (T2 and T3). For 8D spacing, the attenuation of power oscillations is weaker, and T2 still exhibits visible peaks with a time delay relative to T1. The difference in power attenuation between 4D and 8D spacing is also evident in the corresponding spectra. This behavior is because, as we showed in Fig. 8, the shear instability mechanism that damps low-frequency velocity fluctuations becomes weaker at further downstream.'

Minor Comments

(1) Line 21: I would suggest qualifying this statement with the caveat that it depends on the wind direction. Or at least clarifying that this is due to how wind turbines are sited within a wind farm.

Reply

We agree with the reviewer that whether turbines in a wind farm are waked depends on wind direction.

Revison

We have rewritten lines 21-22 to clarfy this point.

'In a wind farm, wind turbines can fully or partially operate in the wake regions of those upstream, depending on the wind direction.'

(2) Line 53: The terrain at AWAKEN is not mountainous. In Fig. 1, the valleys and peaks are pronounced because of the colorbar. The greatest elevation difference looks like it is just over 100m over a distance of several kilometers.

Reply

According to Debnath et al. [7], the terrain is a fluviatile plain with a gradual west-to-east slope.

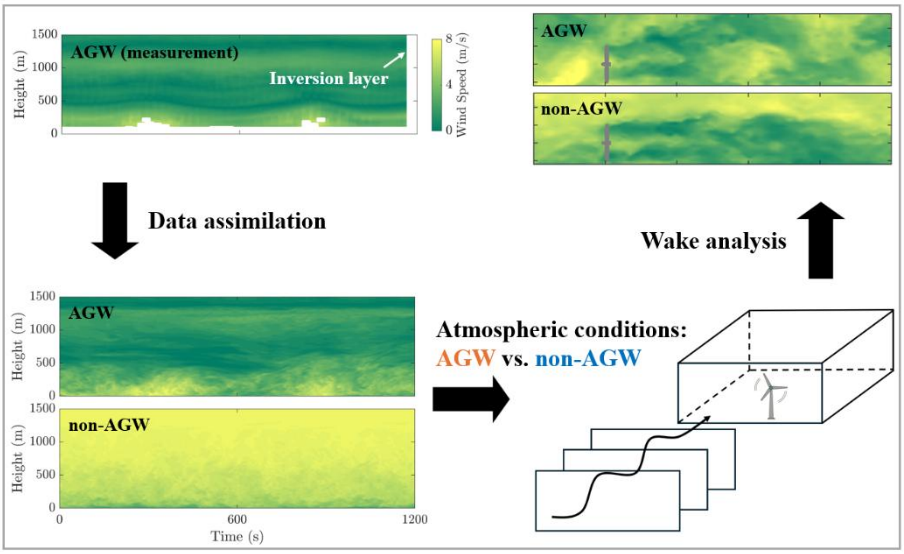
Revison

In the revised draft, we have removed *'The west-east mountainous terrain in this region causes multiple AGW events'* and added '*The terrain is fluviatile plain with a gradual west-to-east slope (Debnath et al., 2022).*' in the caption of Fig. 1.

(3) Figure 3: I appreciate that the contours are explained in the caption, but I think there needs to be a color bar because there are colors other than green and yellow and it is difficult to interpret values in between.

Revison

We have replotted Fig. 3 (shown here as R-Fig. 6 and renumbered as Fig. 2 in the revised draft) and added a colorbar for clarity.



R-Fig. 6: Flow chart of the present measurement-driven LES study.

(4) Line 91: "onshore terrain" is too vague. State what the land is used for near AWAKEN. Is it agricultural? Or perhaps shrubland?

Reply

As have been noted in our reply to Minor Comment (2), the terrain at AWAKEN is a fluviatile plain with a gradual west-to-east slope.

Revison

We have removed *'onshore terrain'* and added '*The terrain is fluviatile plain with a gradual west-to-east slope (Debnath et al., 2022).*' in the caption of Fig. 1.

(5) Line 104: This claim should have a citation.

Reply

We have added references in the revised draft to show that, beyond three rotor diameters downstream, the present actuator-disk model is consistent with both wind-tunnel experiments [8] and actuator-line simulations [9].

Revison

We have added the reference from Wu & Porté-Agel [8] and Stevens et al. [9] in lines 110-112.

'While the effects of the nacelle and tower are neglected, this method has demonstrated good agreement with wind tunnel measurements and high-fidelity numerical simulations in the far wake region (Wu and Porté-Agel, 2011; Stevens et al. 2018), which primarily influences wind farm flow characteristics.'

(6) Line 106: Is the turbine operating at 9 rpm specifically for this case? Typically, there is a range of rpm turbines operate at from cut-in to rated.

Reply

Yes, we simplified the turbine operating condition to a constant 9 rpm, as our study is a case study of single-turbine wake dynamics rather than a simulation of the exact AWAKEN wind farm.

Revison

We have discussed the simplification of turbine operating condition in lines 112-115.

'The turbine operates at a constant rotational speed of nine rotations per minute (9 rpm). This simplified operating condition is used because the present work serves as a preliminary investigation of a single turbine, rather than a detailed simulation of the exact AWAKEN wind farm.'

(7) Line 125: Please provide a citation for the definition of wake meandering for the interested reader.

Revison

We have added the work of Ainslie [10] as a reference in lines 134-135.

'Wake meandering refers to large-scale oscillations of the wake flow driven by low-frequency spanwise and vertical velocity fluctuations in the atmospheric flow (Ainslie, 1988).'

(8) Figure 7: the legend entry for non-AGW almost makes it look like there is a

third entry. Please rearrange the entries for clarity.

Revison

We have modified the non-AGW entries as suggested by the reviewer.

(9) Line 184-185: delete “in the instantaneous wake flow”.

Revison

We have deleted these words.

(10) Figure 9: I would suggest using a different colorbar for velocity and TKE (Fig. 6).

Revison

We agree with the reviewer, and we have used different colormaps for velocity (see Fig. 9) and TKE (see Fig. 6) in the revised draft.

References

[1] Sato, K., Tateno, S., Watanabe S., and Kawatani Y., 2012. Gravity wave characteristics in the Southern Hemisphere revealed by a high-resolution middle-atmosphere general circulation model, J. Atmos. Sci., 69, pp.1378-1396.

[2] Wise, A.S., Arthur, R.S., Abraham, A., Wharton, S., Krishnamurthy, R., Newsom, R., Hirth, B., Schroeder, J., Moriarty, P. and Chow, F.K., 2025. Large-eddy simulation of an atmospheric bore and associated gravity wave effects on wind farm performance in the southern Great Plains, Wind Energy Science, 10(6), pp.1007-1032.

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[4] Feng, D., Li, L. K., Gupta, V., and Wan, M., 2022. Componentwise influence of upstream turbulence on the far-wake dynamics of wind turbines, Renewable Energy, 200, pp.1081–1091.

[5] Smits, A. J., McKeon, B. J. and Marusic, I., 2011. High–Reynolds number wall turbulence, Annual Review of Fluid Mechanics, 43(1), pp.353-375.

[6] Hutchins, N., Chauhan, K., Marusic, I., Monty, J. and Klewicki, J., 2012. Towards reconciling the large-scale structure of turbulent boundary layers in the atmosphere and laboratory, Boundary-layer meteorology, 145(2), pp.273-306.

[7] Debnath, M., Scholbrock, A. K., Zalkind, D., Moriarty, P., Simley, E., Hamilton, N., Ivanov, C., Arthur, R. S., Barthelmie, R., Bodini, N., et al., 2022. Design of the American Wake Experiment (AWAKEN) field campaign, Journal of Physics: Conference Series, vol. 2265, p.022058.

[8] Wu, Y.-T. and Porté-Agel, F., 2011. Large-eddy simulation of wind-turbine wakes: evaluation of turbine parametrisations, Boundary-layer meteorology, 138, pp.345 – 366.

[9] Stevens, R.J., Martínez-Tossas, L.A. and Meneveau, C., 2018. Comparison of wind farm large eddy simulations using actuator disk and actuator line models with wind tunnel experiments. Renewable energy, 116, pp.470-478.

[10] Ainslie J. F., 1988. Calculating the flowfield in the wake of wind turbines, Journal of Wind Engineering Industrial Aerodynamics, 27, pp.213–224.