University of British Columbia

UBCO-UL NSERC Alliance Grant “Reduced-Order Models of Wind Farm Induction and Far-Field Wake Recovery”

Response to Reviewer 2

Exec. S. Stipa - March 7, 2024

We would like to thank the reviewer for the time dedicated to revising the paper. We proceed with answering and clarifying, where possible, the proposed comments.

Our response, denoted in black, is shown below, while the reviewer's comments are denoted in blue. Please refer to the track changes document for a detailed overview of the changes made to the manuscript.

Global blockage effects: The authors are drawing strong conclusions on the mechanisms that cause the global blockage effect. They attribute the velocity deceleration upstream of the wind farm either to a gravity wave-induced pressure gradient or to flow confinement (e.g., Lines 41-43, Lines 185-187, Lines 289-291, Lines 344-345, Lines 388-389). I agree that flow confinement and gravity waves may play a role in these cases; however, the deceleration of the wind upstream of the wind farm can also be due to other mechanisms that are likely present in these simulations but that are not discussed here (Bleeg and Montavon, 2022; Sanchez Gomez et al., 2023). In fact, the authors clearly show that other mechanisms (i.e., not gravity wave-induced velocity deceleration) are responsible for more than 50% of the velocity deceleration upstream of the wind farm and gravity-wave-induced blockage is secondary (Figure 6).

Our statements on the mechanism causing global blockage effects are based on the findings from a number of recent studies that emphasize the critical role played by atmospheric gravity waves (see for example Devesse et al., 2023; Lanzilao and Meyers, 2023; Stipa et al., 2023). However, we acknowledge that these may have not been presented in the clearest way and the manuscript has been heavily revised. Moreover, some additional comments can be made to clarify the specific points addressed by the reviewer.

First, we do not fully agree with the definition of local and global blockage given by Bleeg and Montavon (2022). In particular, they define local blockage as the blockage from immediate neighbors, while global blockage is given by wind-farm-scale blockage effects. In our opinion, this definition does not allow to clearly distinguish between individual turbine induction (and its cumulative effect) and effects related to atmospheric stability. In fact, while local induction acts mainly at the turbine scale, it also has an impact — albeit small — at the wind farm scale (this is clearly shown in Stipa et al., 2023). Conversely, stability effects are only observable at the wind farm scale. For this reason, we refer to global blockage as the flow deceleration produced by the presence of stability above the ABL. When also individual turbine induction and its cumulative effect are considered, i.e. local blockage, the entirety of the upstream flow deceleration can be captured Devesse et al. (2023); Stipa et al. (2023). It is not clear to us what are the other physical mechanisms beyond gravity-wave-induced blockage the reviewer is referring to. We certainly acknowledge that global blockage will show a dependency on the wind farm geometry, wind shear, wind veer, and stability inside the ABL, but we argue that the physical mechanism still remains that described by, e.g. Devesse et al. (2023); Lanzilao and Meyers (2023); Stipa et al. (2023) and in the present paper.

Another important point is that focusing solely on global blockage only covers half of the underlying physics. In fact, the higher the blockage the more favorable the pressure gradient is inside the wind farm. As shown in Figure 11 of the revised paper, those conditions characterized by higher blockage are far from experiencing the lowest overall wind farm efficiency, a testament of the importance of unfavorable and favorable pressure gradients produced by stability both upstream and inside the wind farm.

To specifically address the reviewer's comment on flow confinement and AGWs contribution to blockage, we highlight the statement added at lines 605-609 of the track changes document. In particular, global blockage effects is always due to flow confinement, which is an alternative way of referring to the AGW-induced pressure gradient. The two are in fact uniquely related, as mathematically shown in Section 2.2 (this section has been heavily modified, please see the track changes document). To further expand on this, in the rigid lid cases, global blockage is generated in the exact same manner as in the full AGW solution, with the only difference being that flow confinement is restricted to that produced when $\eta = 0$. This implies that the flow is horizontally divergence free in the rigid lid case (i.e. on wall-parallel planes),

while continuity is satisfied on pliant surfaces defined by η in the full AGW solution (i.e. curved surfaces, locally coincident with the vertical streamline displacement). Notably, both induce global blockage due to flow confinement or, alternatively, to stability effects above H, with the rigid lid being a limiting case for $\Delta\theta \rightarrow \infty$ and/or $\gamma \rightarrow \infty$. Additions to the revised manuscript regarding these aspect can be found at lines 328-333, 605-609 and 730-737 of the track changes document.
Finally, Figure 6 (which became Figure 7 in the revised manuscript) indicates that global blockage corresponding to $\eta = 0$ (rigid lid) yields the majority of the blockage observed when the flow confinement accounts for the AGW solution in the free atmosphere. In both cases, global blockage is produced by flow confinement.

To better elucidate the relation between fully neutral conditions (no stratification) in which blockage is only produced by turbine induction, the rigid lid condition which only considers the effect of H, and the full AGW solution, which also considers the effect of $\Delta\theta$ and γ, we have calculated the non-local, wake and wind farm efficiencies for each of these cases. These are defined by Lanzilao and Meyers (2023) and are reported in Section 4.2 of the revised manuscript. Besides enhancing our understanding of detrimental (global blockage) and beneficial (turbine wake recovery) effects produced by stability, we arrive to the same conclusion of Section 4.2 of Bleeg and Montavon (2022), i.e. that the rigid lid approximation might overestimate wind farm power even more than fully neutral conditions, even though it captures some of the global blockage effects. This emphasizes the importance of modeling the entirety of free atmosphere stability effects and not only global blockage.

Rigid-lid approximation: The authors use the rigid-lid approximation throughout the manuscript; however, it is not clear what is the purpose of using such a simplified and unrealistic modeling approach. In Lines 83-85, the authors suggest the rigid-lid approximation may be useful for use in engineering parameterizations. What do the authors mean by engineering parameterizations? Also, the rigid-lid approximation is tested here neutral boundary layer flow, which is unrealistic compared to the atmospheric boundary layer. For example, Bleeg and Montavon (2022) show that neglecting the temperature stratification in the capping inversion and troposphere misrepresents the blockage effect.

By engineering parametrizations we refer to low-cost reduced order models such as the 3LM Allaerts and Meyers (2019) or the MSC model (Stipa et al., 2023). Reduced order models based on the rigid lid approximation are currently being used in industry tools to model global blockage effects. This aspect is also reported in Section 4.2 of Bleeg and Montavon (2022), where it is referred to as the symmetry plane method. The two things are in principle equivalent.

The last comment made by the reviewer implies that the basic idea of the approach described in the manuscript is not clear. To rectify this, a clarification about the purpose of investigating the rigid lid approximation has been added to the revised manuscript and can be found at lines 591-593 of the track changes document. In particular, the fact of imposing a certain height and displacement of the upper boundary in the LES is automatically equivalent to consider a certain inversion strength and free atmosphere lapse rate (see Section 2.2 of the revised manuscript, where this is explained using a simple analytical model). This means that the effect of stability above the ABL can be implicitly modeled within the ABL if the vertical boundary layer displacement η corresponding to the specific conditions under investigation (wind farm geometry, and unperturbed velocity and potential temperature profiles) are known. This is because the heterogeneous pressure gradient produced by flow confinement due to η and arising from the AGW solution in the free atmosphere have to be coincident. As a consequence, the rigid lid approximation is not equivalent to a case without thermal stratification, where the upper boundary should be placed ideally very far from the ground. Instead, it is a limiting solution corresponding to very large stratification above the ABL. The purpose of studying this approximation is to understand how it compares with current industry practice (i.e. fully neutral conditions) and with the full AGW solution. The same limiting solution has been studied by Bleeg and Montavon (2022) (cases 3 vs 5 and 3b vs 5b).

Line 153-154: Why are the wind farm and upper layer characterized by the same background velocity? This assumption virtually discards the effect from shear and the large gradients associated with the atmospheric surface layer.

The analytical model presented in Section 2.2 is only used to explain the unique relation that exists between the pressure $p^\star$ and the inversion displacement η. The assumption of constant velocity inside the boundary layer allows the original 3LM equations to be easily rewritten in terms of η instead of η_1 and η_2 by summing up the continuity equations in the wind farm and upper layer. Doing the same within the original 3LM equations would only be possible in Fourier space and the conclusions would be more difficult to see. However, the generality of our reasoning can be readily proved by noticing that, once η is known, Equation 10 is not required anymore and pressure can be obtained by solving Equation 9.

Figure 2: The divergent color map is not centered at 0, making it very difficult to distinguish between positive and negative inversion displacements.

The reviewer's comment has been implemented in the revised manuscript.

Lines 299-300: I would argue that the AGW-modeled and AGW-resolved approaches do not predict almost the same pressure perturbation for the subcritical case (Figure 3a). Differences in the pressure perturbation field between the AGW resolved and modeled approaches are at least on the order of 10% upstream of the wind farm.

We agree with the reviewer's comment and the paragraph has been rephrased.

Lines 307-312: The differences upstream of the wind farm are just as large (or larger) than the differences at the domain outflow. However, the hypothesis presented by the authors does not address these differences. The flow upstream of the wind farm is outside and downstream of the fringe region and these differences are still large.

We agree with the reviewer's comment and added additional explanation in the revised manuscript. In particular, the following considerations can be made. The AGW-modeled and MSC model feature the exact same η, but a different level of fidelity inside the boundary layer. Hence, the same η does not lead to identical pressure and velocity perturbations. Conversely, the AGW-modeled and AGW-resolved cases use the same model inside the ABL, but η is slightly different, as it comes from the MSC model in the former and it is resolved in the latter. As a consequence, mass and momentum conservation show some differences in the perturbation velocity and pressure. This aspects have been added to the revised manuscript (see lines 518-529 of the track changes document).

Lines 344-345: The authors conclude that flow confinement is responsible for blockage to a lesser extent than gravity waves. However, Figure 6 clearly shows that the velocity deceleration with gravity waves is less than twice as large as the deceleration in the rigid-lid simulations. Thus, it seems flow deceleration from gravity wave-induced pressure gradients is not the main cause for blockage in these simulations. Also, I would argue that flow confinement is not the only cause for blockage in the rigid-lid case.

We realized that the way the sentence was written was misleading. In particular, blockage is in both cases given by flow confinement effects. In the AGW-modeled cases, the flow confinement is produced by an inversion displacement calculated with linear theory using the MSC model (thus accounting for the full AGW solution). In the rigid lid case, the value of η has been set to zero according to an infinitely high stability above the boundary layer (which is an approximation). Figure 6 (corresponding to Figure 7 in the revised manuscript), shows that assuming an infinitely strong stability accounts for the majority of the global blockage effect observed when modeling also the inversion displacement. The sentence has been rephrased according to these considerations (see lines 605-609 of the track changes document).

The authors mention that the LES domain should extend to one or more wavelengths in each direction (Line 113). However, extending the LES above 10-12 km in the atmosphere means you are performing simulations above the tropopause, where the temperature stratification is very different from the constant lapse rate assumed within the troposphere. Is gravity wave propagation sensitive to having multiple thermally stratified layers like in the atmosphere compared to a single constant lapse rate? This might be out of the scope of the paper but is something to consider.

This is correct. While the validity of the Boussinesq approximation for such tall domains has been demonstrated (see "Response to Reviewer 2" from `https://wes.copernicus.org/preprints/wes-2023-40/wes-2023-40-AR2.pdf`), the assumption of linear lapse rate might be somewhat strong for certain LES setups where λ_z is very large. However, although undoubtedly worthwhile to be kept in mind for the future, this aspect has not been addressed yet in the context of wind farm LES. The only study that looked at non-uniform lapse rate in the free atmosphere has been performed by Devesse et al. (2022), who extended the 3LM to model these types of conditions. The authors state that a non-uniform lapse rate can play a big role in some cases. However, the 3LM model is based on linear theory and cannot account for other important physical phenomena such as gravity wave break-up and non-linear interaction.

References

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