

Response to Reviewer 1 for Manuscript egusphere-2026-2292

Wave-phase-aware model implementation in WRF-LES v3.8.1 for turbulence-resolving simulations of turbulent flow over monochromatic waves

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Response to Reviewer 1

General Comment

This paper compares different ways to represent surface gravity waves in simulations of the atmospheric boundary layer with an LES framework. The most accurate method is the wave-phase-resolved moving-boundary formulation which the authors refer to as the moving-wave model (MOW), wherein the grid follows the wave surface and explicitly computes the resulting pressure forces. This is compared to two wave phase-aware models that assume a flat sea surface but include wave amplitude and phase effects through addition of effective bottom stress terms that account for the unresolved pressure variations. These are referred to as the wave drag model (WDM) and windward potential flow model (WPM) that employ different methods to estimate the pressure effect. The most novel aspect of the paper is the implementation of these three schemes in the same WRF-LES code base, thus allowing for a fair comparison of the methods without subjecting the comparison to differences in numerical methods related to the underlying LES approach. The results should be very useful for the WRF community, and the idea is an excellent framework for comparisons of different parameterizations in ocean and atmospheric models. The paper should be published after the authors respond to the following comments.

Response to General Comment: We thank the reviewer for the positive assessment of the manuscript and for the constructive comments.

We have revised the manuscript extensively in response to the reviewer’s suggestions. In particular, we have made the model comparisons more quantitative, reorganized and enlarged the key figures and axes to improve readability, and revised the discussion to more clearly identify the differences and limitations of each approach.

To follow the original terminology of [Ayala et al. \(2024\)](#), we have also replaced the designation “Windward Potential Flow Model (WPM)” with “Moving Surface Drag Model (MOSD)” throughout the manuscript and the accompanying source code.

We also updated the velocity sampling height used in the MOSD pressure-stress calculation to follow the original model formulation of [Ayala et al. \(2024\)](#). In the original implementation, the velocity entering the pressure-stress formulation is sampled at a height corresponding to the horizontal LES resolution, which in the present configuration is $z = \Delta x$. Our initial implementation instead sampled this velocity at the third vertical grid point, consistent with the sampling height used in its original equilibrium wall-stress model. We have now corrected this distinction and use $z = \Delta x$ for the MOSD pressure-stress calculation. The comparative wall stress continues to use the common first-off-wall framework described in Section 2.3, while the native MOSD wall model is documented separately in Appendix A. All simulations affected by this change were rerun, and the corresponding results in the manuscript were updated accordingly. The revised MOSD source code incorporating this change is provided with the revised submission.

We have addressed the reviewer’s comments individually below.

Comment 1

The paper reads as if the authors set out to prove that the phase-aware models agree with the phase-resolved model, leading to overly subjective evaluation of the results with phrases like, “slightly overestimates”, “show good agreement”, “exhibit slight deviations”, “with minor differences”, “agree closely”, “slight deviations”, or “slightly underestimate”. Since the methods are already published in the peer-reviewed literature, there is no need to prove their accuracy one way or another. This paper should be used as an opportunity to present an unvarnished and quantitative comparison of the models so that future users are aware of the pitfalls for the methods.

- (a) *The most important figure in the paper is Figure 4a which compares the nondimensional form stress as a function of wave age and steepness for the different methods. The plot is too small, and the axes emphasize the variability due to wave slope rather than that due to wave age, for which it is noted that “WPM and MOW show good agreement across all wave steepness levels”. This plot should only compare results with $ak = 0.10$ since that enables a fair comparison between all three models as well as to results in the literature. There is no need to show results of the phase-aware models with different ka because there is no validated solution. The variability with steepness and the fact that the phase-aware models agree can be quantified by simple scaling analyses. I don’t think Figure 4b is needed or it should be in a separate section (see #2 below).*
- (b) *Another example is the comparison of the contours of wave-induced streamwise velocity in Figure 7. There is no reason to believe that these should be the same among the three methods given the fundamentally different character of the bottom boundary condition when comparing the MOW to the other methods. Nevertheless, the authors go to great lengths to show how they are similar through use of rescaled color axes.*

Response 1: Our goal is to implement the three wave modeling approaches within the same open-source LES code and to report the differences objectively. This comment is helpful in identifying further opportunities to achieve this goal.

We agree that the original manuscript placed too much emphasis on qualitative statements regarding agreement among the models. We have therefore revised the manuscript to make the comparison more quantitative. We have replaced the subjective characterization of model agreement with quantitative descriptions of the differences among the models and have revised the discussion to more clearly identify their limitations.

- (a) In the original manuscript, Figure 4 combined the results for all three wave steepnesses and presented the original and modified WDM formulations in separate panels. In the revised manuscript, the primary pressure-drag comparison is presented in the enlarged Figure 2 using only $ak = 0.10$, for which results from all three models and DNS data are available (e.g., [Sullivan et al., 2000](#); [Kihara et al., 2007](#); [Yang and Shen, 2010](#)). The corresponding values are reported in Table 2. Results for $ak = 0.18$ and 0.25 are now discussed separately and summarized quantitatively in Table 3. The modified WDM analysis previously shown in Figure 4b has been moved to Appendix B, where the behavior of the original formulation is also examined through the scaling given by Equation (B1).
- (b) We agree that the wave-induced velocity fields should not be expected to coincide because MOW explicitly resolves the moving wave boundary, whereas WDM and MOSD represent its effects through parameterized forcing. We have therefore substantially revised the interpretation of these results. Statements in the original manuscript that the wave-phase-aware models exhibit similar behavior or reproduce the MOW spatial pattern have been removed. The revised discussion now

states that the wave-phase-aware predictions differ substantially from MOW in both magnitude and spatial structure, with amplitudes at least one order of magnitude smaller, and that they do not quantitatively reproduce the detailed wave-induced flow resolved by MOW.

The common-scale comparison is retained in revised Figure 4 to show the magnitude difference directly. The rescaled view in Figure 5 is included only to make the much weaker structures predicted by WDM and MOSD visible; its different scale is identified explicitly and is not used as evidence of agreement with MOW.

Comment 2

Introduction of the exponential decay function to improve the WDM formulation seems very ad-hoc and not very useful because all it appears to do is eliminate the negative values of the form stress for high wave age. I would recommend eliminating it unless there is a clear quantitative justification for its form and the coefficients.

Response 2: We thank the reviewer for raising this concern.

We agree that the original presentation did not sufficiently justify the proposed correction and could give the impression that it was introduced simply to eliminate negative pressure-drag values. We have therefore moved this analysis from the main model comparison to Appendix B and substantially expanded its justification.

First, we now examine the scaling of the original WDM formulation in Equation (B1). This analysis shows why the magnitude of the negative pressure drag can increase again once the wave speed exceeds the local airflow velocity, rather than continuing to decrease with wave age as indicated by the available DNS results. The exponential function is therefore introduced as an empirical damping of this behavior. Importantly, the correction does not eliminate negative pressure drag or change the direction of momentum transfer. Because the damping function is strictly positive, it preserves the sign predicted by the original WDM formulation; as shown in Figure B1, the corrected values remain negative at the larger wave ages but have reduced magnitudes.

We have also clarified the selection of the coefficients. The reference wave age $(c/u_*)_0 = 10$ corresponds approximately to the onset of the regime in which the original WDM prediction becomes increasingly negative, while $\alpha = 1.4$ was selected empirically by varying α and comparing the resulting simulations with the available DNS data for $ak = 0.10$. The corresponding damping factors are now reported explicitly for each simulated wave age. The same parameters are then applied without retuning to the $ak = 0.18$ and 0.25 cases.

Finally, we now describe this correction as a practical empirical modification restricted to the range examined here, $8 \leq c/u_* \leq 24$, rather than as a general treatment of strongly swell-dominated conditions. We also explicitly acknowledge the lack of independent DNS data at the larger steepnesses and note that the high wave age treatment of [Aiyer et al. \(2024\)](#) may be more appropriate outside this range.

Comment 3

The differences between the WRF-LES-WDM and LESGO-WDM results in Figures 2 and 3 are attributed to “differences in the numerical schemes employed by the LES codes.” Given that the premise of the paper is precisely to avoid these types of differences through comparison of methods in the WRF framework, this validation should be removed as it detracts from the novelty of the paper.

Response 3: We thank the reviewer for this comment.

We agree that the WRF-LES-LESGO comparison detracted from the central model intercomparison and did not constitute a formal verification. We have therefore removed the comparison and the associated figures and discussion from the revised manuscript. The main results now focus directly on comparing MOW, WDM, and MOSD within the common WRF-LES framework.

Comment 4

This is more of an aside given that these terms are likely already established in the literature, but it's odd to me that the models are referred to as phase-resolved vs phase-aware. Since the phase-aware models amount to linearizations of the bottom boundary conditions by imposing effective pressure stresses at $z = 0$ rather than the kinematic boundary condition at $z = h$, this is a finite-amplitude effect, not a phase effect. Thus, it is the amplitude effect that is not resolved, while the phase effect is resolved. My interpretation may stem from use of the term to distinguish between phase-resolved wave models like FUNWAVE, SWASH, and NHWAVE and action balance models like SWAN and WAVEWATCH III which are phase-averaged.

Response 4: We thank the reviewer for this clarification.

We agree that the principal distinction between the approaches is whether the finite amplitude wave geometry is explicitly represented in the atmospheric domain. Our terminology follows its use in the wind-wave LES literature, where models such as WDM and MOSD are referred to as wave-phase-aware, while approaches that explicitly represent the moving wave boundary are referred to here as wave-phase-resolved. We recognize that this terminology differs from its use in the wave modeling community.

To avoid ambiguity, we have revised Section 2.2 to define the terminology explicitly. MOW explicitly represents the moving wave geometry and resolves the associated pressure response, whereas WDM and MOSD retain the wave-phase information over a flat lower boundary and parameterize the wave-induced pressure stress.

Comment 5

The phase-aware models appear to be presented using the formulations in the original papers which not only makes it difficult to directly compare them, but the same variables are used to represent different quantities from one method to the next. The authors should write all methods using the same variables and note where they differ. For example, in the paper $u_r = u - u_s$ for MOW and WPM while $u_r = u - c$ for WDM. I suggest using different variables for these two relative quantities, noting that u_r for WDM is the velocity in a wave-following frame. One way to unify the methods is by writing all three in terms of the total bottom stress

$$\tau_{i3}^{\text{Total}} = \tau_{i3}|_{\text{wall}} + f_{pi}, \quad (1)$$

where the effective bottom stress due to pressure, $f_{pi} = 0$ for MOW and, for WDM and WPM,

$$f_{pi} = -C_D U_i U^\Delta \left(n_k \frac{\partial h}{\partial x_k} \right)^n H \left(n_j \frac{\partial h}{\partial x_j} \right), \quad (2)$$

where, for WDM, $n = 1$ and

$$C_D^{\text{WDM}} = \frac{P}{1 + Q(ak)^2} ak, \quad (3)$$

$$U_i^{\text{WDM}} = u_i, \quad (4)$$

$$U^{\Delta, \text{WDM}} = |\vec{u} - \vec{c}|, \quad (5)$$

$$n_k^{\text{WDM}} = \frac{\vec{u} - \vec{c}}{U^{\Delta, \text{WDM}}}. \quad (6)$$

For WPM, $n = 2$ and

$$C_D^{\text{WPM}} = \frac{1}{\pi}, \quad (7)$$

$$U_i^{\text{WPM}} = U^{\Delta, \text{WPM}} \frac{1}{|\nabla h|} \frac{\partial h}{\partial x_i}, \quad (8)$$

$$U^{\Delta, \text{WPM}} = |\vec{u} - \vec{C}|, \quad (9)$$

$$n_k^{\text{WPM}} = \frac{\vec{u} - \vec{C}}{U^{\Delta, \text{WPM}}}. \quad (10)$$

This more clearly shows how both methods are similar in how they parameterize the pressure force on the flow by the waves. Additionally, it is clear that, for the two methods,

$$U_i U^{\Delta} \left(n_k \frac{\partial h}{\partial x_k} \right)^n \sim \begin{cases} u_* |u_* - c| ak, & \text{WDM,} \\ |u_* - c|^2 (ak)^2, & \text{WPM,} \end{cases} \quad (11)$$

which shows why the steepness is included in C_D^{WDM} so that both methods are of the same order of magnitude. Writing the methods in this way avoids the need to define the drag force per unit area, $F_{d,i}$, for each method (it might be useful to write the equations as they appear in the papers in the appendix).

- (a) The drag forces per unit area are dimensionally inconsistent since, as written, they are in units of force per unit volume.
- (b) The addition of the directional term $(\nabla h/|\nabla h|)$ in Equation 24 based on the need to include $\text{sgn}(u - c)$ is not clear, since the direction of ∇h is not necessarily related to that of $\vec{u} - \vec{c}$. Furthermore, $(\nabla h/|\nabla h|)$ is a vector whereas Equation 24 is already written for vector component i . It would also be helpful simply to include this term in the description of the WDM method rather than as an entire paragraph in a different section. The details of why the form in the original WDM paper does not have the term can be included in an appendix.
- (c) I suggest using scaling to estimate the magnitude of the terms in each phase-aware formulation to show why an exponential decay is needed for the WDM model to behave correctly for large wave age.
- (d) The wall-stress terms should also be written in a consistent way since they can all be written as $\tau_{i3}|_{\text{wall}} = C_d U_r u_{r,i}$. An estimate of the magnitude of $\tau_{i3}|_{\text{wall}}/f_{pi}$ would be helpful to understand the relevance of this wall-stress term for the phase-aware models. It would also be helpful to evaluate the extent to which using the filtered velocity versus the original velocity makes a difference when evaluating the bottom stress. The reader may see the use of the filtered velocity as necessary when in reality the differences are negligible.

- (e) *Evaluation of the log law at a height $\Delta z/2 - h$ to compute the drag coefficient in Equation 16 appears to be inconsistent with the idea that the phase-aware models represent a linearized representation of the wave kinematics by evaluating everything at $z = 0$ rather than at $z = h$. Furthermore, the factor $\Delta z/2 - h$ implies a limiting grid size below which the method fails, which makes the method fundamentally inconsistent with the philosophy of LES which should converge to the “exact” filtered solution with grid refinement.*

Response 5: We thank the reviewer for these detailed and very useful suggestions.

We have substantially reorganized Sections 2.2 and 2.3 to place the three approaches within a common notation and surface momentum framework. We now distinguish the airflow velocity relative to the local wave-surface orbital velocity for MOW, $\mathbf{u}_{r,s} = \mathbf{u} - \mathbf{u}_s$ (Equation (5)), from the horizontal velocity in the wave-following frame, $\mathbf{u}_{r,c}^m = \mathbf{u}_h - \mathbf{c}^m$, with $m \in \{\text{WDM}, \text{MOSD}\}$, (Equation (7) for WDM and Equation (11) for MOSD). The sampling heights and any additional filtering are specified separately for WDM and MOSD. The total surface momentum transfer is now written in Equation (2) as the sum of the unresolved wall stress and parameterized wave-induced pressure contribution. The original model-specific wall-stress formulations have been moved to Appendix A.

- (a) We have corrected the dimensional inconsistency. The WDM and MOSD pressure contributions are now written directly as kinematic stresses, with units of $\text{m}^2 \text{s}^{-2}$, rather than being described as forces per unit area while including a division by grid-cell depth. Revised Section 3 separately explains how these stresses enter the WRF momentum tendencies.
- (b) We have removed the additional $\nabla h/|\nabla h|$ directional factor from the WDM formulation. In revised Equation (9), the windward-facing condition is defined using the unit vector of the phase-relative velocity, $\mathbf{e} = \mathbf{u}_{r,c}^{\text{WDM}}/|\mathbf{u}_{r,c}^{\text{WDM}}|$. The sign of each pressure-stress component is treated separately through $\text{sgn}(u_{r,c,i}^{\text{WDM}})$, following [Aiyer et al. \(2024\)](#). This description is now included directly in the WDM subsection. The updated WDM source code is provided with the revised submission.
- (c) A scaling analysis of the WDM pressure-stress term has been added in Appendix B. Equation (B1) shows its dependence on wave steepness and phase-relative velocity and explains why the original formulation can predict increasingly negative pressure-drag magnitudes after the wave speed exceeds the local airflow velocity. This analysis provides the motivation for the empirical wave age-dependent damping discussed there.
- (d) The unresolved wall stresses are now written consistently in Equation (13), and all three approaches use the common roughness-based drag coefficient in Equation (14). In the statistically stationary channel, the total imposed stress is u_*^2 , so the relative wall-stress contribution follows directly from $\tau_{\text{wall}}/u_*^2 = 1 - D_p/u_*^2$. Thus, the values reported in Tables 2 and 3 quantify the relative importance of the pressure and wall-stress contributions. For example, for $ak = 0.10$, D_p/u_*^2 ranges from -0.325 to 0.259 for WDM and from -0.022 to 0.060 for MOSD across the examined wave ages in this work, indicating that the unresolved wall stress provides the larger contribution over these cases.

We have also clarified the filtering notation. All resolved WRF velocities are LES-filtered quantities. For the parameterized pressure stress, WDM uses the grid-scale velocity at the first off-wall level without an additional test filter, whereas MOSD uses the velocity at $L = \Delta x$ with the additional 2Δ test filter prescribed in its original formulation. We retain these model-specific pressure-stress sampling strategies rather than introducing modified formulations, and no claim is made that the additional test filter is required for WDM.

- (e) We acknowledge the reviewer’s concern regarding the use of $\Delta z/2 - h^\Delta$ in the native WDM wall-law. The wave-elevation offset is analogous to displacement-height formulations commonly

employed in turbulent boundary-layer modeling, including LES of flows over rough surfaces (Jackson, 1981). Although such formulations are well established, their implementation in LES wall models can introduce significant log-layer mismatch under certain conditions (Shin et al., 2025). In the present study, however, the native WDM wall-law is not used in the comparative simulations. Instead, all three models employ the same roughness-based wall-stress framework, with the drag coefficient evaluated using the distance $\Delta z/2$ from the lower boundary, as described in Section 2.3. The original WDM formulation is retained in Appendix A for completeness.

Comment 6

The grid resolutions for all three methods should be identical. Indeed, the phase-aware models might have the advantage that they can be used with coarse grids (although I do not see how this could be the case). However, with different grid resolutions it is impossible to attribute differences due to the parameterization or the numerics, which is precisely the premise of the paper.

Response 6: We thank the reviewer for raising this important point.

We agree that using identical grid resolutions would, in principle, be preferable for isolating differences associated purely with the parameterizations. However, the wave-phase-resolved and wave-phase-aware approaches impose fundamentally different requirements on the vertical grid near the surface.

For WDM and MOSD, the wave geometry is not explicitly resolved in the vertical direction, and the first off-wall grid point must remain above the prescribed wave surface. We therefore require $a_{\max} < 0.85\Delta z/2$. With $\Delta z \simeq 2.5$ m, $0.85\Delta z/2 \simeq 1.06$ m, which remains slightly larger than the maximum wave amplitude, $a_{\max} \simeq 1.044$ m, allowing the same 22-level grid to be used for all wave steepnesses considered.

In contrast, MOW explicitly resolves the moving wave surface and therefore requires sufficient vertical resolution of the wave geometry and the associated near-surface pressure field. To assess whether the same 22-level grid could be used for MOW in the present configurations, we repeated simulations at $c/u_* = 8$ and 10 for all three wave steepnesses. The resulting normalized pressure-drag values are compared below with those obtained using the standard 32-level MOW grid (see Table 1 below). Across the six cases, the 22-level grid reduces D_p/u_*^2 by 87.5–92.4% relative to the corresponding

Table 1: Comparison of the normalized pressure drag, D_p/u_*^2 , obtained from MOW using the standard 32-level vertical grid and the 22-level vertical grid used for WDM and MOSD.

c/u_*	ak	32-level grid	22-level grid
8	0.10	0.092	0.009325
8	0.18	0.240	0.029291
8	0.25	0.382	0.047638
10	0.10	0.108	0.008172
10	0.18	0.283	0.023763
10	0.25	0.403	0.040035

32-level MOW simulations. We therefore retain the 32-level grid for MOW in the present study, with a near-surface vertical spacing of approximately $\Delta z \simeq 0.12$ m. Conversely, applying this near-surface resolution to WDM and MOSD for the present wave amplitudes would violate the requirement that the prescribed wave remain below the first off-wall grid point. Thus, for the configurations considered here, a common vertical grid cannot simultaneously satisfy the numerical constraints used for both model classes. This two-grid comparison is intended as a sensitivity check demonstrating that the 22-level

grid is not adequate for the MOW pressure-drag predictions examined here; it is not a systematic grid convergence study and does not establish a general minimum vertical resolution for MOW. We have added this vertical grid sensitivity analysis to the Appendix of the revised manuscript (Appendix C).

These grid constraints also clarify the scope of the comparison. MOW is used here with the finer vertical grid needed to resolve the moving wave geometry and associated pressure response, whereas WDM and MOSD are applied on the coarser grid for which the prescribed wave remains vertically unresolved. We therefore employ model-specific but case-independent vertical grids: 32 levels for MOW and 22 levels for WDM/MOSD. Accordingly, the present comparison evaluates the complete modeling approaches under their respective numerical constraints rather than a parameterization-only comparison at identical vertical resolution.

Comment 7

Following the previous comment, the time-step size should be the same for all three models. All viscous or turbulent stress terms (including the bottom drag) are discretized implicitly in WRF to ensure stability in the presence of possibly very small layer heights. Similarly, the phase-aware models should be implemented implicitly in WRF if they are to represent a useful contribution to the code base. Otherwise, it is easy to see how the time-step size needed for stability of the phase-aware pressure terms could become vanishingly small for small layer heights, strong winds, fast waves, and/or steep slopes.

Response 7: We thank the reviewer for raising this important numerical consideration.

We agree that using the same outer Runge–Kutta time step is necessary for a controlled comparison. We have therefore repeated the simulations using the same Δt for all three models under each wave condition. A time step of $\Delta t = 0.01$ s is used for MOW, WDM, and MOSD for all cases except $c/u_* = 8$ and $ak = 0.10$, for which $\Delta t = 0.005$ s is used for all three models. The corresponding acoustic Courant numbers remain below the practical WRF stability limit. These settings and the associated Runge–Kutta and acoustic stability constraints are now documented at the end of Section 5.

We have also clarified the numerical implementation in Section 3 and revised Figure 1 accordingly. The unresolved wall stress is computed through `vertical_diffusion_2` in `module_diffusion_em.F`, following WRF’s vertical diffusion treatment. In contrast, the parameterized WDM and MOSD pressure-stress contributions are evaluated in their respective physics routines and added explicitly to `ru_tendf` and `rv_tendf` before the Runge–Kutta momentum update.

We agree that a semi-implicit treatment of the parameterized pressure stress could improve robustness for substantially smaller layer heights or more strongly forced wave conditions. However, we have not introduced this additional modification in the present study. Instead, we retain the explicit implementation and demonstrate that it remains stable over the wave regimes and grid configurations examined here using the matched time steps described above. We now state this implementation choice clearly and limit our conclusions to the tested parameter range. Developing and evaluating a semi-implicit formulation would be a useful extension for applications requiring finer near-surface grids or more extreme forcing.

Comment 8

It is stated that the phase-aware models reduce the vertical grid resolution requirement by approximately 10–20%. This conclusion could only be substantiated with a rigorous grid resolution study and subsequent quantification of error reduction as a function of simulation time for the

different methods.

Response 8: We thank the reviewer for pointing this out.

We agree that the previously stated 10–20% reduction in vertical grid resolution requirements was not supported by a systematic grid refinement study, and we have therefore removed this quantitative claim and the related general comparison of computational cost.

As discussed in our response above, the two model classes have different near-surface resolution requirements. We therefore retain only the qualitative conclusion that the wave-phase-aware formulations can be applied on coarser near-surface grids than MOW for the cases considered here. We do not claim a general grid reduction percentage or computational speedup, since establishing the minimum reliable resolution and corresponding cost for each model would require a dedicated grid refinement study.

Comment 9

I do not see how the MOW approach costs four times as much as the other approaches for the same grid resolution. There is essentially very little overhead when computing the terms needed for the moving bottom, especially since the metric terms are computed at every time step regardless of whether the bottom moves. I am also not aware of the need for more precision when the bottom moves in WRF.

Response 9: We thank the reviewer for pointing this out.

We agree that the original fourfold cost estimate was not based on a controlled comparison at the same grid resolution and therefore should not have been attributed to the overhead of the moving-bottom formulation. The observed wall-clock times also reflect differences in vertical resolution and the physical integration time required for statistical convergence. We have therefore removed the fourfold cost estimate. The revised manuscript reports only the observed wall-clock-time range for the simulations and does not interpret it as an intrinsic cost difference among the models.

Comment 10

Minor:

- (a) *Equation 2: The SFS tensor is typically defined in terms of spatial averages.*
- (b) *Please report the Courant number when describing the time-step size needed for stability. I note that WRF incorporates a splitting technique in which the acoustic modes are linearized at each time step and advanced forward in time with smaller time steps with sub-stepping.*

Response 10: We thank the reviewer for these comments.

- (a) We agree that the original notation was ambiguous because the overbar was also used for temporal averaging. We have therefore removed the overbar notation and now define the deviatoric component of the SFS stress tensor inline. We have also clarified that the resolved variables are spatially LES-filtered at the grid scale Δ , while $\widehat{(\cdot)}$, $\overline{(\cdot)}$, and $\langle \cdot \rangle$ denote additional box filtering at the test-filter scale 2Δ , temporal averaging, and horizontal spatial averaging, respectively.
- (b) We have expanded the time-stepping description to include both the outer RK3 and acoustic mode stability constraints. The acoustic substep is defined as $\Delta\tau = \Delta t/n_s$, with $n_s = 4$ for

MOW and $n_s = 6$ for WDM and MOSD. The acoustic Courant number,

$$C_r^{\text{ac}} = \frac{c_s \Delta t}{n_s \Delta x},$$

is now reported. For $\Delta t = 0.01$ and 0.005 s, its maximum values are approximately 0.27 and 0.13 for WDM and MOSD and 0.40 and 0.27 for MOW, respectively. These values remain below the practical acoustic stability limit of $C_r^{\text{ac}} = 0.5$ (Skamarock et al., 2008). We also clarify that the same outer RK3 time step is used for all three models under each corresponding wave condition.

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