# Reply to Reviewer #1

*We sincerely thank the reviewer for the careful evaluation of our manuscript and for the constructive comments and suggestions, which have helped us to improve the quality, clarity, and scientific presentation of the paper. We have carefully considered all comments and revised the manuscript accordingly. Please find our detailed replies to the reviewer's comments below, with our responses shown in blue.*

## General Comments

This study investigates stratospheric gravity waves generated by Typhoon Soudelor (2015) using WRF simulations to evaluate the sensitivity of various physical parameterization schemes. While a high-resolution simulation of such a well-observed case is potentially valuable, the current manuscript lacks scientific novelty and fails to meet the rigorous standards established in previous studies.

The fundamental issue is that while the authors observe high sensitivity among different schemes, they provide little to no physical explanation for these variations. Furthermore, the experimental design is poorly balanced: although diabatic heating is identified as the primary driver of TGWs, the sensitivity tests are disproportionately focused on PBL schemes rather than a comprehensive range of Cumulus Parameterization (CP) or microphysics options. Additionally, the absence of spectral analysis for convective sources and wave propagation conditions relative to the mean flow leaves the study incomplete. Consequently, I cannot recommend the manuscript for publication in ACP in its current form. Detailed comments for improvement are provided below.

*We thank the reviewer for this detailed and constructive assessment of our manuscript. We agree that, in the original version, the physical interpretation of the differences among the parameterization schemes was not sufficiently developed. In the revised manuscript, we have therefore substantially expanded the discussion of the physical mechanisms responsible for the simulated sensitivity, with particular emphasis on how differences in diabatic heating, convection, cloud microphysics, and boundary-layer processes affect the generation and propagation of typhoon-induced gravity waves.*

*We also agree that the scope and rationale of the sensitivity experiments needed to be clarified. In response to the reviewer's concern, we have revised the description of the experimental design and added new simulations to expand the assessment of the parameter space. These additional experiments include further combinations of cumulus parameterization and microphysics schemes, allowing us to better evaluate the role of diabatic heating and convective processes in the simulated stratospheric gravity wave response.*

*In addition, we have strengthened the gravity wave diagnostics in two important respects. We now illustrate the localized S-transform analysis with a representative example showing the retrieved wave amplitudes and horizontal and vertical wave-*

*lengths. We have also added a direct perturbation-based estimate of gravity wave momentum flux from the simulated wind fields. These additions allow us to move beyond vertical velocity variability alone and to assess both the spectral characteristics and the vertical flux of horizontal momentum carried by the simulated waves.*

*Furthermore, we have revised the manuscript to more clearly state the scientific objective and novelty of the study. Rather than presenting the simulations only as a comparison among parameterization schemes, we now frame the work as an assessment of how different representations of typhoon convection and related heating structures influence the characteristics of stratospheric gravity waves in a well-observed typhoon case. We believe that these revisions, together with the additional simulations and expanded physical interpretation, have considerably strengthened the manuscript and addressed the reviewer's main concerns.*

**Specific Comments**

**1. Insufficient Literature Review and Theoretical Framework**

- The manuscript overlooks several key studies on TGWs. Source mechanisms and stratospheric TGWs have been extensively investigated using spectral analysis, which accounts for wave propagation from the cloud top to target altitudes under various background flows. The current analysis appears insufficient, likely due to a lack of familiarity with these established methodologies.

*We thank the reviewer for emphasizing the established source-to-stratosphere spectral framework used in previous studies of typhoon-generated gravity waves. We have expanded the Introduction to discuss studies that relate the convective source spectrum to the wave spectrum at stratospheric altitudes and account for selective propagation under different background flows, including (Kim et al., 2007, 2009; Kim and Chun, 2010).*

*We have also revised the description and presentation of our spectral diagnostics. The gravity wave analysis is not based only on bulk vertical velocity variability, but also includes a localized S-transform analysis of the simulated vertical velocity field. For each analysis location, the S-transform is used to identify a locally dominant wave component and to estimate its amplitude and associated horizontal and vertical wavelengths.*

*To make this analysis more transparent, we have added a new example figure for the Goddard–MYJ simulation at $t = 27$ h and $z = 40$ km. The figure shows the original vertical velocity field, its magnitude, the reconstructed dominant-wave contribution, the diagnosed S-transform amplitude, and the corresponding horizontal and vertical wavelengths. This illustrates explicitly that the spectral analysis provides localized wave information beyond domain-integrated or variance-based statistics.*

*We have further clarified why the S-transform is suitable for the present application. Typhoon-generated gravity waves occur as transient and spatially localized wave packets in a horizontally inhomogeneous environment. A localized spectral method is therefore useful for identifying how the dominant wave amplitude and scale vary across the simulated domain.*

*At the same time, we now state the methodological scope more explicitly. The S-transform used here is not equivalent to a full direction-resolved frequency–wavenumber or phase-speed analysis of propagation from the convective source to the upper stratosphere. The diagnosed stratospheric spectrum represents a subset of the source spectrum that may have been modified by background winds, stability, and critical-level filtering. We identify a joint source-spectrum and multi-level propagation analysis as an important extension of the present work.*

- One significant contribution of TGWs to typhoon dynamics is missing from the Introduction. TGWs generate divergence in the UTLS, leading to compensatory convergence at the typhoon center, which enhances typhoon intensity. This feedback loop is a crucial aspect of TGW research, and references investigated this subject should be included and discussed to provide proper context.

*We thank the reviewer for highlighting the possible feedback of typhoon-generated gravity waves on tropical cyclone dynamics. We have added a short discussion to the Introduction noting that gravity wave momentum transport and the associated divergence may interact with the upper-tropospheric outflow and secondary circulation of a TC and may thereby influence storm evolution.*

*We have formulated this discussion cautiously. The present study diagnoses gravity wave activity, spectral characteristics, and momentum flux, but it does not calculate wave-induced divergence, momentum flux convergence, or a resulting feedback on TC intensity. We therefore introduce this mechanism as an important aspect of the broader scientific context rather than as a feedback demonstrated by the present simulations.*

- Since TGWs are a subset of convective gravity waves (CGWs), characterizing them through source spectra and propagation conditions is essential for a comprehensive understanding of their behavior. Although the depth of the convective source and the level of maximum heating were discussed earlier (Figs. 8 and 9), their physical significance was not explicitly detailed. This relationship can be explained by the resonance between the natural modes of internal GWs defined by the dispersion relation and the vertical harmonics of the convective forcing. The reference investigated regarding this issue should be included and discussed to provide proper context.

*We thank the reviewer for this important comment. We agree that the original manuscript reported differences in the altitude and depth of latent heating without explaining their physical significance in sufficient detail.*

*We have expanded the discussion accompanying Figs. 8 and 9. The revised text now explains that the vertical heating profile can be represented as a superposition of vertical harmonics and that the resulting gravity wave response depends on how these harmonics project onto natural gravity wave modes that satisfy the dispersion relation. Differences in heating depth, peak altitude, and profile shape can therefore modify both the efficiency of wave excitation and the distribution of vertical wavelengths in the source spectrum.*

*We have also clarified that the relationship is not one-to-one: the diagnosed heating depth does not uniquely determine a single gravity wave wavelength, because the response additionally depends on the horizontal and temporal scales of the forcing, atmospheric stratification, background winds, and subsequent propagation. We therefore reformulated the previous statement that the shallower Goddard heating profiles directly imply shorter vertical wavelengths. The* *revised interpretation is expressed in terms of modal projection and preferential coupling rather than claiming that a discrete resonance was directly diagnosed. Relevant references on thermally forced gravity wave spectra and vertical heating structure have also been added (Alexander et al., 1995; Beres et al., 2002, 2004; Kim and Chun, 2010).*

## 2. Unbalanced Experimental Design

- Given that diabatic heating is the primary source of TGWs, sensitivity experiments should prioritize various CP and microphysics schemes over PBL schemes. I strongly recommend reducing the emphasis on PBL variations and instead expanding the range of cloud microphysics and CP options. A comparison of Figures 4, 5, and 6 clearly indicates that the inclusion of a CP scheme produces large-scale features that are vital for TGW representation.

  *We agree with the reviewer that the original experimental design placed disproportionate emphasis on PBL sensitivity relative to microphysics and cumulus parameterization. We have therefore expanded the experiment set in two ways. First, Thompson microphysics has been added as a third microphysics option, in addition to WSM6 and Goddard. Second, the Grell–3 cumulus parameterization is now tested in combination with all three microphysics schemes. These additional simulations allow us to assess whether the effect of outer-domain cumulus parameterization is robust across different microphysical representations, rather than being inferred only from the WSM6-based comparison.*

  *We have also revised the rationale for retaining the PBL experiments. The PBL schemes are used to sample uncertainty in the low-level thermodynamic and momentum supply to the storm, rather than being treated as parameterizations that directly control gravity-wave generation. Through their effects on turbulent mixing, inflow, moisture convergence, and convective organization, they can indirectly modify the structure and intermittency of diabatic heating and hence the gravity wave source.*

  *The revised experiment design therefore addresses three complementary pathways: microphysical control of condensate and latent heating structure, outer-domain cumulus control of the environment supplied to the convection-permitting nest, and PBL control of the low-level forcing of deep convection. We have revised the Methods and Discussion to make this rationale explicit and to interpret the individual PBL-scheme differences cautiously.*

- In the current setup, the CP scheme experiment uses the WSM6 microphysics scheme instead of the Goddard scheme (Table 1), despite the latter generally showing superior performance. To ensure robustness, the authors should at least include an experiment combining Goddard and Grell-3.

  *We agree that the original WSM6-only cumulus comparison did not provide a sufficiently robust basis for drawing conclusions about the influence of Grell–3. We have therefore added simulations combining Goddard microphysics with Grell–3 in the outer domain.*

  *In addition, we have added corresponding Thompson–Grell–3 simulations. The revised experiment set consequently allows the influence of Grell–3 to be examined across all three microphysics schemes rather than being inferred from a single WSM6-based comparison.*

*The new results also show that the response to Grell–3 is not uniform across the microphysics configurations. We have therefore revised the manuscript to avoid the previous statement that cumulus parameterization consistently weakens convection or gravity wave activity. Instead, we now describe the effect as configuration dependent and emphasize the interactions among microphysics, PBL formulation, and outer-domain cumulus parameterization.*

**3. Quantitative Analysis of TGWs**

- The study relies on the standard deviation of vertical velocity to represent TGW activity. However, the dynamical importance of stratospheric TGWs lies in their momentum deposition upon dissipation. Without analyzing wave breaking and dissipation, wave activity alone does not provide a complete picture of their impact on large-scale flow. A standard frequency-wavenumber spectral analysis is required to determine which portions of the source spectrum are filtered out and which propagate into the middle atmosphere.

*We agree with the reviewer that vertical velocity variability alone is not sufficient to characterize the dynamical importance of the simulated gravity waves. In response, we have substantially extended the gravity wave diagnostics and now distinguish clearly between the spectral characterization of the wave field and the diagnosis of momentum flux.*

*First, we retain the localized S-transform as a diagnostic of the dominant gravity wave component. It provides the local wave amplitude together with the corresponding horizontal and vertical wavelengths. We now document this analysis explicitly with a new example figure showing the original vertical velocity field, the reconstructed dominant-wave contribution, and the retrieved wavelength information for a representative Goddard–MYJ simulation.*

*Second, we have added a direct perturbation-based estimate of gravity wave momentum flux derived from the WRF wind fields. A large-scale horizontal background is removed using an FFT-based horizontal filter, yielding the perturbation fields $u'$, $v'$, and $w'$. The local momentum flux fields are calculated as $\rho u'w'$ and $\rho v'w'$. For the inter-simulation comparison, we then evaluate the magnitude of the vector formed by their horizontal means,*

$$|\mathrm{GWMF}| = \sqrt{\langle \rho u'w' \rangle^2 + \langle \rho v'w' \rangle^2},$$

*where the angle brackets denote horizontal averaging over all valid grid points in an inner-domain analysis region.*

*The revised manuscript includes both a representative horizontal and vertical cross-section of this diagnostic and a comparison of the domain-mean and radially averaged GWMF among the physics configurations.*

*This direct perturbation-based calculation provides a more direct and physically interpretable estimate of net gravity wave momentum flux than vertical velocity variance alone. However, we agree that momentum flux is not identical to momentum deposition. The new diagnostic does not constitute a full diagnosis of wave breaking, flux divergence, or gravity wave drag. We now state this limitation explicitly and avoid claiming that the present analysis quantifies the resulting forcing of the large-scale circulation.*

*We also clarify that the localized S-transform is not presented as a complete frequency–wavenumber source-to-stratosphere filtering analysis. It is used to characterize the locally dominant wave scales, whereas the perturbation-based calculation is used for the actual momentum flux diagnosis.*

- The authors select TGWs based on a specific magnitude threshold. However, as noted above, large-amplitude waves can be less significant if they are filtered at lower altitudes. Conversely, smaller-amplitude TGWs that may survive in the upper level can deposit significant amount of momentum forcing when they dissipated there, due to the inverse relationship between density and drag. Therefore, the analysis should consider the full spectrum of amplitudes rather than focusing exclusively on the strongest waves.

*We agree that a fixed vertical velocity-amplitude threshold is difficult to justify as the basis of the main physical interpretation. We have therefore revised the analysis so that the central conclusions no longer depend on the previous threshold of* $0.3\ m\ s^{-1}$.

*The new S-transform example figure presents the continuous diagnosed amplitude and wavelength fields rather than only a thresholded subset. For the statistical S-transform analysis, the diagnosed wave properties are weighted by the local wave amplitude so that stronger components contribute more strongly without completely excluding weaker components.*

*In addition, the new direct momentum flux calculation is evaluated from all valid perturbation-field grid points in the inner-domain analysis region. No additional vertical velocity-amplitude threshold is applied to select the wave population used for the GWMF calculation.*

*This revised approach avoids using an arbitrary cutoff as the basis of the main conclusions and includes a broader range of diagnosed wave amplitudes. The previous threshold-sensitivity material has therefore been removed from the main analysis.*

**4. Lack of Physical Interpretation**

- The manuscript offers almost no physical reasoning for the differences observed between various schemes. Simply stating that results differ is not a scientifically meaningful contribution. Each parameterization is built on distinct theoretical or empirical foundations; the authors must discuss the simulation results in the context of these underlying physical differences to provide insight into why certain schemes perform differently.

*We thank the reviewer for this important criticism. We agree that the previous manuscript described the differences among physics configurations more clearly than it explained their physical origin. We have therefore revised both the Methods and Discussion.*

*In the model-description section, we now summarize the scheme properties that are directly relevant to convection and gravity wave generation. In particular, we discuss how WSM6 and Goddard differ in their treatment of mixed-phase hydrometeors, particle conversion, and sedimentation; how the Grell–3 cumulus scheme modifies the thermodynamic* *environment supplied to the convection-permitting inner domain; and how local and nonlocal PBL closures affect turbulent mixing, inflow, moisture convergence, and convective organization.*

*We have also expanded the interpretation of the results by explicitly linking these scheme characteristics to the diagnosed cloud structure, latent heating profiles, and stratospheric gravity wave response. The revised discussion identifies three main pathways: microphysics control of the magnitude and vertical distribution of latent heating, indirect modification of resolved convection by outer-domain cumulus parameterization, and PBL control of the low-level thermodynamic and momentum supply to convection.*

*The revised Results section also includes a direct perturbation-based gravity wave momentum flux diagnostic. This analysis shows that the configuration dependence is present not only in vertical velocity variability and spectral properties, but also in the vertical flux of horizontal momentum. At the same time, the ordering of the simulations is not identical across the latent heating, wave-amplitude, and momentum flux diagnostics. We now use this result to emphasize that heating magnitude alone does not uniquely determine the stratospheric wave response.*

*Where the available diagnostics do not permit unique attribution to an individual process, we now state this limitation explicitly and present the proposed mechanisms as physically consistent interpretations rather than definitive process-level proof. We have also moderated the interpretation of individual PBL-scheme differences because their effects depend on interactions with microphysics, storm evolution, and the environmental flow.*

## References


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