We thank the referee for the assessment and for the remaining important comments, which we address in detail. Below, we repeat the reviewer's remarks in red italics, and add our respective responses in normal text.

The authors addressed most of my comments, and the revised manuscript looks good. But I have a few important comments:

1) *L245 (Revised Version): The relationship between the sign of the EP flux divergence and wave drag is opposite. When the EP flux converges, or when the divergence is negative, easterly momentum is transferred, which is wave drag. If divergence is reduced (convergence increases), wave drag increases and leads to a weaker mean westerly flow.*

Thank you for the comment. For EP flux divergence, more negative values indicate stronger convergence of the EP flux, corresponding to enhanced wave drag through the transfer of easterly momentum. Conversely, more positive EP flux divergence anomalies indicate reduced convergence and therefore weaker wave drag. As stated in line 245, the diagnosed EP flux divergence anomaly is predominantly positive, which is consistent with reduced wave drag and is largely aligned with the zonal-mean zonal wind anomaly.

The remaining discrepancies, particularly in the lower stratosphere within the forced region, arise because the zonal-mean wind anomaly is not determined solely by resolved wave forcing represented by the EP flux. In these regions, the imposed subgrid-scale orographic gravity-wave (SSO GW) drag plays a dominant role in shaping the momentum budget.

We have clarified this point in the revised manuscript by explicitly referring to Figure A2, which shows the forced SSO drag in the different experiments. This clarification has been added around line 244 of the revised manuscript to emphasize the role of SSO GW drag in determining the zonal-mean zonal wind anomaly.

2) Overall, the discussion lacks information on how GW forcing relates to the signals we observe. For example, the authors repeatedly point out the increasing frequency of C5. However, how does amplified GW forcing in each hotspot lead to such an increase in frequency, especially for C5? Why is the geometry of C5 special? Additionally, despite the emphasis on geometry-conditioned responses in the introduction, the subsequent analysis of each cluster appears to focus more on common features than on different signals depending on geometry. For instance, the WCVC signal of C2, C3, C5, and C6 is addressed repeatedly, yet I could not find an explanation of how each cluster's SPV "geometry" relates to the signal. Since the authors emphasized the importance of geometry-conditioned responses, it seems important to discuss how each cluster's SPV geometry relates to the WCVC and FSDC rather than discussing common geometries. If these discussions need further studies, then at least some hypotheses and open questions are needed

Thank you for this insightful comment. A full process-based attribution of how localized episodic GW forcing modifies stratospheric dynamics would require dedicated event-based diagnostics. Such analyses typically involve threshold-based identification of high-intensity events and detailed wave-mean flow interaction diagnostics (e.g., as in Sacha et al., 2021), which lie beyond the scope of the present climate-scale sensitivity study.

In this work, we intentionally adopt a complementary approach: we apply a localized enhancement of SSO GW drag by a factor of 10 in specific regions within long climate simulations. This design aims to isolate the statistical imprint of enhanced GW forcing on SPV variability, rather than to attribute individual events. Importantly, SSO GW drag is highly intermittent and spatially variable even in the control simulations, with local amplitudes that can naturally vary by an order of magnitude. The imposed forcing therefore does not introduce an unrealistically new regime, but instead increases the probability that such strong GW forcing occurs, making its influence detectable in a climatological framework.

Regarding the increased frequency of cluster C5, this cluster belongs to the single-vortex class and is characterized by the weakest planetary wave-1 (PW1) amplitude and the strongest PW2 amplitude among the single-vortex geometries (see discussion in lines 397–406, 528, and 533 of the revised manuscript). Enhanced GW drag preferentially suppresses upward-propagating PW1 activity, thereby favouring SPV states with reduced PW1 dominance. This makes the C5 geometry particularly susceptible to increased occurrence under enhanced GW forcing. The mechanism by which localized forcing reduces PW1 activity, via compensation mechanism and modified wave propagation conditions, is examined in detail using finite-amplitude wave activity (FAWA) diagnostics in Mehrdad et al. (2025a), and is therefore not repeated here.

We further hypothesize that the enhanced GW drag perturbs the SPV edge locally through increased small-scale wave breaking and secondary instabilities, thereby promoting geometry-specific PV redistribution rather than a uniform vortex response (Coy et al., 2024). This mechanism is briefly discussed in lines 386–388 of the revised manuscript, where additional context has been added to improve clarity and ensure consistency with the observed geometry-conditioned responses.

Finally, the geometry-conditioned response framework isolates individual SPV geometries and diagnoses how the imposed forcing projects onto each configuration. This conditional approach enables the extraction of physically meaningful signals from the highly variable stratospheric background. Importantly, the dynamical response associated with one geometry can oppose that of another; when these responses are aggregated, they may cancel, yielding a weak or ambiguous mean signal. By conditioning on geometry, we therefore recover responses that are dynamically coherent but masked in the combined statistics. As discussed in lines 429–438 of the revised manuscript, the diagnosed PV mixing preferentially follows the SPV edge, reflecting a geometry-dependent interaction between the forcing and the vortex structure on climate time scales. This edge-aligned mixing constitutes a shape-related response and provides further evidence for the role of secondary instabilities in mediating the stratospheric adjustment. This interpretation has been clarified explicitly in lines 433–434 and 437–438 of the revised manuscript.

In summary, the objective of this study is not a process-resolving attribution of individual GW events, but a climate-scale assessment of how enhanced localized GW forcing reshapes SPV variability through geometry-dependent pathways. We have therefore expanded and clarified the discussion, as detailed above, to better articulate this interpretation. A fully causal, event-based characterization of the interaction between localized GW forcing and SPV geometries would require dedicated high-frequency diagnostics and would thus be beyond the scope of the present study. Nevertheless, the additional clarifications provided here ensure that the role of SPV geometry in mediating the response to GW forcing is explicitly addressed, consistent with the conceptual framework introduced in the manuscript.

References:

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