Review of "Propagation of gravity waves and its effects on pseudo-momentum flux in a sudden stratospheric warming event"

By In-Sun Song et al.

Recommendation: Accept with minor revisions

This is a nicely done, comprehensive study of gravity wave (GW) propagation from tropospheric sources into the middle atmosphere under background wind conditions prevailing during the sudden stratospheric warming of 2009. The authors use a ray tracing model to show how spatial inhomogeneity and evolution of the background flow alters the characteristics of propagating GW; and how this 4D (x, y, z; t) propagation model differs from 2D (z; t) propagation in many nontrivial ways.

The paper is acceptable for publication essentially in its present form. Specific comments below should be addressed to clarify certain points and correct minor errors of grammar and syntax.

Specific Comments (page, line)

(1, 16) "may have profound impacts": Why "may"? GW are the main component of the eddy momentum budget in the mesosphere and above. I would have written "have profound impacts".

(1, 24) "radiatively-driven latitudinal temperature gradient across the two poles"→ pole-to-pole radiatively-driven latitudinal temperature gradient".

(2,1) "Irreversible heat and heat fluxes": This does not make sense. I believe you mean to say "irreversible heat and *momentum* flux *divergences*".

(3, 1) "predominance of non-dissipative wave-mean interaction": "Predominance" overstates the case. Kruse and Smith (2018) stated (their abstract) that "Non-dissipative accelerations are non-negligible and influence a [mountain wave's] approach to breaking, *but breaking and dissipative decelerations quickly develop and dominate the subsequent evolution*" (my italics). Perhaps you meant to say "importance" or "relevance" of non-dissipative interactions? In any case, irreversible changes of the background flow ultimately occur only through dissipation.

(3, 18) "GW activities" → GW activity (this is the standard usage, "activity" here being used as a collective noun).

(4, 19) "where Λ_ns (n = 1, … N) denote": This is awkward and confusing because the trailing "s", which I believe is intended to denote a plural, could be taken to be part of the symbol. The standard usage for mathematical symbols is that they do not normally takes an "s" to denote plural. Replace this with "where Λ_n (n = 1, … N) denote…" Note that this occurs many other times through the paper when referring to Λ_n and other symbols. Please do a thorough check.

(7, 19) “Then, τ_{def}s are computed” → Then, τ_{def} is computed. See previous comment. In standard usage τ_{def} stands for all cases of the “deformation” time scale. No trailing “s” needed.

(10, 4) Figure 3: I would delete panels (a) and (d) of this figure, which do not contain any information that cannot be succinctly explained in the text. On the other hand, there could be a little more discussion of the interesting panels (b)-(c) and (e)-(f). In particular, panel (b) indicates that OGW flux, F_p, is well organized in space in a single ensemble member. I presume this is due to the fact that F_p is strongly constrained by the OGW source parameterization, which depends explicitly on orography and low-level wind. By contrast, organization of F_p for the NOGW case only emerges in the ensemble because any single ensemble member is completely stochastic (panels (e) vs. (f)).

(10, 32) “but being weakened” → but is much weakened.

(10, 32) “Transparently shaded areas”: This is confusing. “Transparent” implies no shading at all. I believe you are referring to the areas overlain by gray(ish) shading. If so, please explain more clearly. Better yet would be to use some other means (e.g., cross-hatching) to denote the regions of non-significant differences to avoid confusion with the color shading meant to denote flux magnitude/sign.

(11, 4): “westward F_ps in the 4D are about 10 (28) times enhanced…”: This sentence is nearly incomprehensible. Please break it up into two digestible parts, the first referring to the 10X difference between 4D and 2D models in all but one of the parameterizations; and the second referring to the 28X difference in the case of the WM96b non-orographic parameterization. Also, omit the “s” at the end of F_p, here and in many other instances; see comment (4, 19).

(11, 26) “zonal-mean *k*s”: Here and elsewhere this should be “zonal-mean *k*”; see comment (4, 19).

(12, 6) “thermodynamic forcing terms”: What are these? Are you referring to the dependence on *N*?

(12, 29) “meridional wavenumbers (*l*s)” → Here and elsewhere, “*l*s” should be replaced simply by “*l*”; see comment (4, 19).

(13, 19) Figure 8: This figure shows the striking difference between the 4D and 2D models, especially in the discontinuous (in latitude) appearance of OGW F_p. This is a common problem in comprehensive global models, which usually employ 2D columnar GW parameterizations. Although wave-mean flow interaction will tend to reduce these effects, this does not necessarily happen for the right reasons; see discussion about “compensation” of parameterized vs. resolved wave forcing in Cohen et al. (JAS 2013, 2014). It might be worth mentioning this problem.

(15, 19) Figure 11: You might consider showing panels (a) through (f) in vector form (vector background wind, $\boldsymbol{U}$, vector horizontal group velocity, $\boldsymbol{c}_g$). This would show more clearly the relationship between $\boldsymbol{U}$ and $\boldsymbol{c}_g$; and also (for the intrinsic group velocity) the regions where that vector is non-negligible.

(17, 12) "These enhanced eastward F_ps, if they exist, may induce more rapid recovery of the stratospheric jets, accelerating downward movement of the ES": This is an interesting effect, which would not be captured by the 2D columnar parameterizations used in most comprehensive models. Note again that "F_ps" should be simply "F_p" (no trailing "s").