Response to Reviewer #2's Comments

Comments on "Quasi-10-day wave activity in the southern high-latitude MLT region and its relation to the large-scale instability and gravity wave drag" by Lee et al.

Reviewed by Yosuke Yamazaki, Leibniz Institute of Atmospheric Physics, University of Rostock

This study focuses on the westward-propagating quasi-10-day wave (Q10DW) in the mesosphere and lower thermosphere of the Southern Hemisphere as observed by meteor radars and simulated by the WACCM model. Two WACCM simulations were used, in one of which the model was constrained by the MERRA-2 reanalysis from the surface up to 75 km (EXP75), and in the other simulation the model was constrained similarly but up to 60 km (EXP60). After showing qualitative agreement between the Q10DWs in the meteor radar observations and EXP75 simulation, the authors examined the cause of Q10DW for selected events, and demonstrated that the barotropic/baroclinic instability played a leading role. The authors also compared the Q10DWs in EXP75 and EXP60, and noted that the wave amplitude is generally greater in EXP60. They concluded that the difference resulted from the background atmosphere that is largely controlled by gravity-wave parameterization.

The new findings are the sensitivity of Q10DW to the nudging range adopted in model simulations and the importance of gravity-wave drag in it. I do not have an objection for this paper to be published in Atmospheric Chemistry and Physics. However, I feel that the paper could benefit from some revisions. My specific comments can be found below.

: Thank you for your comments concerning our manuscript "Quasi-10-day wave activity in the southern high-latitude MLT region and its relation to the large-scale instability and gravity wave drag". Those comments are valuable and helpful for improving our investigations and the importance guiding to our research. We have addressed each comment carefully and have made corrections as far as possible. The comments are in bold and our replies are in regular font. We recalculated the amplitude of Q10DW from MRs and identified certain errors in our original analysis. However, these changes do not affect the structure of our manuscript.

Major comments:

Q1. Model-data comparison

Figures 1 and 2 show the Q10DW from meteor radars and WACCM EXP75 simulation, respectively. The disagreement is profound. The patterns of intra-annual variations are different. Also, the wave amplitudes are different by a factor of 3 or so. This makes me wonder whether the radar analysis technique has been properly applied. If yes, and if the discrepancy between the data and simulation exceeds the uncertainties in the radar results, are the simulation results still a good representation of Q10DW? How do the WACCM results compare with the MLS results? It is easier to derive Q10DW using satellite data than radar data. If there is good agreement between the WACCM and MLS results, it would make more sense to present the MLS results instead of the radar results.

A1: We carefully examined our calculation process and identified certain errors in our original analysis. This leads to a uniform adjustment in the overall amplitude of Q10DW. However, it is important to note that the recalculated amplitude of Q10DW from MRs did not alter the seasonal variations as depicted in our manuscript's figures (Figs. 1 and 3). The recalculated amplitude is now found to be approximately one-third to one-half of those obtained from MLS and SD-WACCM. The amplitudes of Q10DW are systematically lower in MRs observations compared to SD-WACCM results. These observations agree with our conclusion that the model reproduces overestimated amplitude of Q10DW. We believe this discrepancy in the amplitude of Q10DW can be attributed to the accuracy of estimated geostrophic wind from MLS data. Figure R1 and R2 show time series of zonal and meridional winds, respectively, measured by meteor radar and geostrophic wind estimated from MLS data in the Antarctic stations (KSS: 62.2°S, 58.8°W and Davis: 68.6°S, 77.9°E) at the altitude of ~90 km. The correlation between meteor radar winds and MLS winds shows a variability of 0.3 to 0.8 depends on year. Notably, the meridional winds component shows lower correlation values than the zonal component. The lower correlation in the meridional wind is likely due to coarse longitudinal resolution of MLS, affecting the accuracy of meridional geostrophic wind estimation. Such differences in the geostrophic wind estimated from MLS data are reported by Rüfenacht et al. (2018) and may account for the observed discrepancies in amplitude of Q10DW.

While MLS data could offer insights into the global structure of Q10DW, the meteor radar observations provide a more precise depiction of Q10DW behavior in the MLT region, especially given MLS's low vertical resolution of about 10 km near the mesopause. Consequently, we adopted an approach begins with meteor radar analysis to investigate local Q10DW activities in the southern high-latitude regions, followed by a detailed analysis using SD-WACCM. Moreover, as shown in Fig. 3 of our manuscript, although the variation of Q10DW/Q10DO amplitudes in EXP75 is not perfectly matched with those in MR for all periods, there is significant agreement during the periods indicated by yellow boxes on the abscissa, which meet multiple criteria as we described in the manuscript.

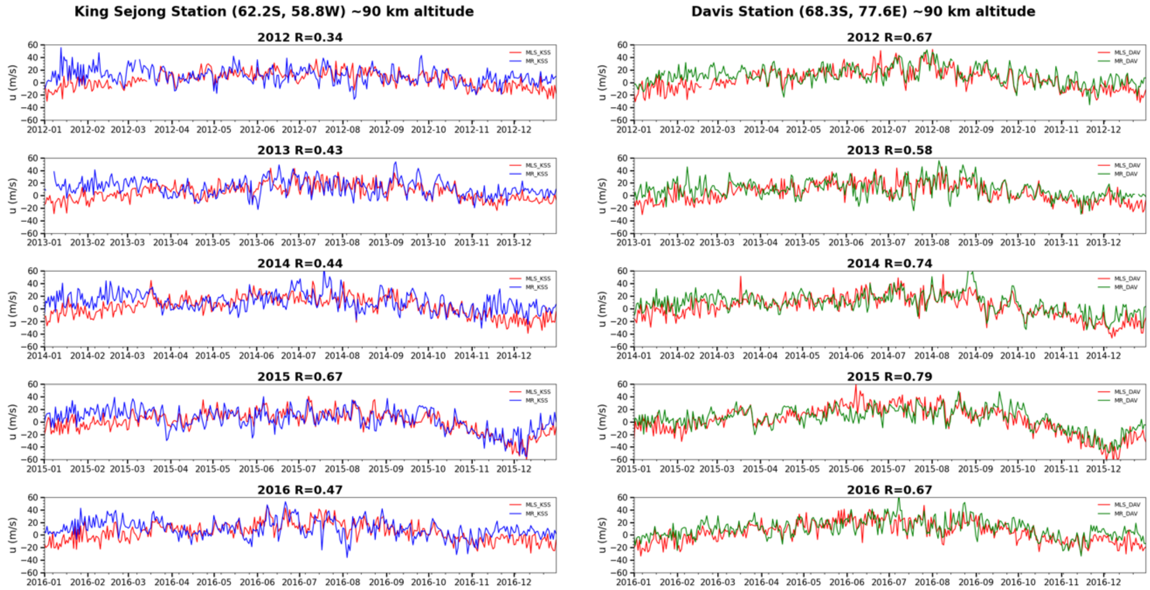

Figure R1. Time series of (blue and green) zonal wind measured from KSS and Davis meteor radar, respectively, and (red and orange) zonal component of geostrophic wind estimated from MLS data near the KSS and Davis, respectively, at the altitude of ~90 km from 2012 to 2016. Correlation coefficients (R) between the meteor radar winds and MLS winds are shown at the top of each panel.

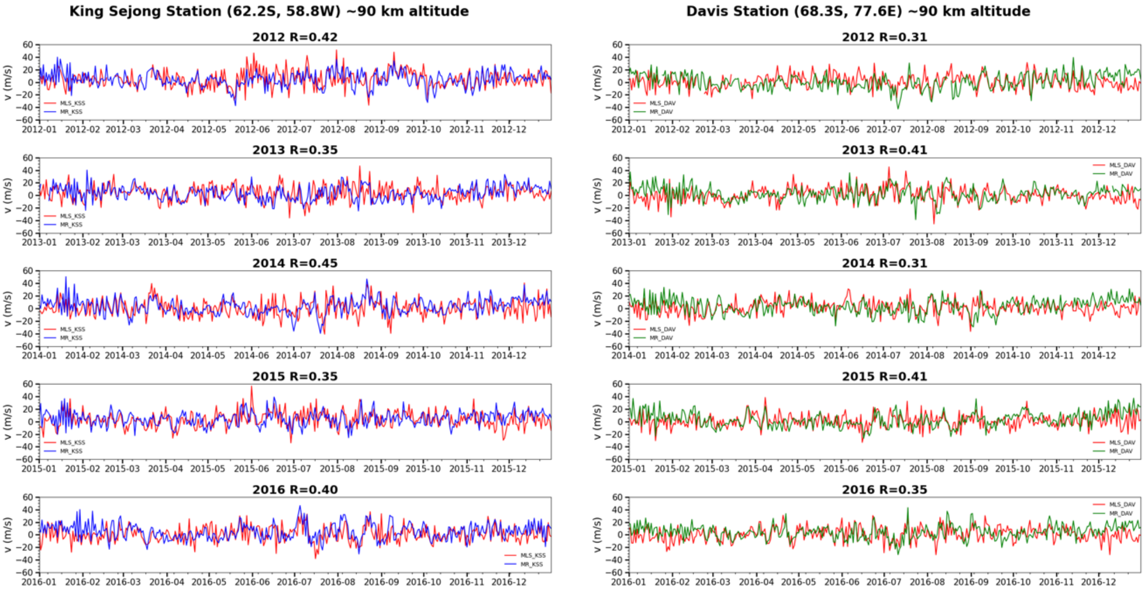

Figure R2. Same as Figure R1, but for meridional wind.

Q2. EXP60 vs EXP75

It is stated that the amplitude of Q10DW in EXP60 is excessive (in Abstract and Summary). However, I do not see evidence to support this statement. Looking at Figures 1, 2 and S2, the amplitude of Q10DW is too small in both EXP75 and EXP60. It is difficult to say which reproduces the observations (Figure 1) better. Again, comparisons with the MLS results might help.

A2: We apologize for any confusion. As mentioned in our response to the first major comment (Q1), we initially miscalculated the amplitude of Q10DW from MRs data, which led to an apparent higher amplitude compared to the model simulations. However, by evaluating again and recalculating these values, we found that the amplitude of Q10DW derived from MR data is actually lower than that in the EXP75, and the difference is even more pronounced when compared to EXP60.

Q3. Introduction

The paragraph starting at l. 65 highlights recent studies on Q10DW. It feels that there are many studies that the authors overlooked especially in the context of the Q10DW response to sudden stratospheric warmings (e.g., Matthias et al., 2012; Yamazaki & Matthias, 2019; He et al., 2020; Wang et al., 2021; Qin et al., 2022;

Yin et al., 2023). It is important to address them, because some of them performed a similar analysis as the authors did in this paper and identified the importance of the barotropic/baroclinic instability.

Matthias et al. (2012) https://doi.org/10.1016/j.jastp.2012.04.004

He et al. (2020) https://doi.org/10.1029/2020GL091453

Qin et al. (2022) https://doi.org/10.1029/2022JD037730

Yin et al. (2023) https://doi.org/10.1016/j.asr.2022.10.054

--- only those which are currently not cited ---

A3: Thank you for pointing out these studies. We agree that the studies you mention should be include into our manuscript to provide a comprehensive background, and thus we added these references to the introduction from line 56 to 117.

Minor comments:

Q4. l. 62 "modulate the periods of tides"

Periods of tides would not change, as tides are defined by their periods (24h, 12h, 8h, etc.) The amplitude of tidal waves can undergo an apparent modulation due to the presence of secondary waves arising from the nonlinear interaction between planetary waves and tides.

Recommended reading

Miyoshi & Yamazaki (2020) https://doi.org/10.1029/2020JA028283

A4: In response to your comment regarding line 62, we revised the sentence to: “In addition, the amplified PWs can interact with tidal waves through nonlinear interactions, resulting ionospheric disturbances during SSWs.” This revision can be found In line 63 of the revised manuscript.

Q5. l. 72 "high-latitude mesosphere and lower thermosphere"

How did they find large Q10DW in the high-latitude region while their data are limited within +/-50 latitude?

A5: We apologize for any confusion. To clarify, we will revise the sentence line 72 from “high-latitude mesosphere and lower thermosphere” to “mid-latitude (40 – 50° latitude) mesosphere and lower thermosphere”. This revision can be found In line 73 of the revised manuscript.

Q6. l. 94 "the amplification mechanism of Q10DW-W1 still has not been investigated"

It may be clarified that this is about the seasonal amplification during equinoxes. As mentioned earlier, the amplification mechanism of Q10DW during sudden stratospheric warmings has been addressed in previous studies.

A6: We are grateful for your comment. To bring more clarify to the sentence, we revised the sentence to “While the amplification mechanism of PWs generated following SSW has been addressed in previous studies (e.g., Qin et al., 2022, Yin et al., 2023), the specific mechanisms driving their seasonal amplification during equinoxes remain less explored.” This revision can be found In line 118–121 of the revised manuscript.

Q7. Figure 1

It would be informative if the geographical coordinates of the radars are mentioned in the figure caption.

A7: We appreciate your suggestion. We agree that including the geographical coordinates of the meteor radars will provide valuable context to the figure. We revised the figure caption to ”…meridional winds observed by MRs at Davis (68.6°S, 77.9°E) and KSS (62.2°S, 58.8°W) for 2012–2016…”.

Q8. l. 392 "F/sgn(A)" (also at l. 473)

What is "sgn"?

A8: The term “sgn” refers to the sign of variable. In this context, “sgn(A)” indicates the sign of variable A (wave activity). To avoid any confusion and provide clarity, we have explicitly mentioned this in the revised manuscript. In lines 445~446, we state: The wave-activity density is shaded in blue and red depending on its sign [$\mathrm{sgn}(A)$].”

Q9. l. 427 "6 April 2015 case"

Unlike the other events, the wave propagation is poleward in the stratosphere. This is a Q10DW event during a final warming event (Yamazaki & Matthias, 2019; Qin et al., 2022). Qin et al. (2022) discussed that the inter-hemispheric propagation of the wave from the Northern Hemisphere was possible because of the phase of the quasi-biennial oscillation.

A9: We are thankful for your intriguing comment. We confirmed that our analyzed case of 6 April 2015 is included in the 2015 final warming event discussed by Yamazaki and Matthias (2019) and Qin et al. (2022). Notably, Qin et al. (2022) reported that the averaged meridional component of Eliassen-Palm Flux from 18 March to 18 April 2015 extends from the stratosphere in the Northern-Hemisphere across the equator to the stratosphere in the Southern Hemisphere (Qin et al., 2022). This finding is consistent with our results. In addition, Figure 9b and 9c in Qin et al. (2022) suggests that the phase of the semi-annual oscillation is also in its westerly phase. This observation, in conjunction with the westerly phase of the QBO in the middle stratosphere, supports the southward propagation of Q10DW from Northern Hemisphere in a wide altitude range from middle to upper stratosphere. To enhance our manuscript, we included additional explanations and the relevant references to this particular aspect in lines 497~502.

Q10. l. 432 "divergent"

It should be "divergence".

A10: We will change the text accordingly. This revision can be found In line 494 of the revised manuscript.

Q11. l. 463 "s>=20"

It is strange that only GWs with high zonal wavenumbers are resolved. Maybe "s<=20"?

A11: As shown in Figs. S3 (b) and (c), our analysis considered two potential contributors to the amplification of Q10DW: 1) nonconservative gravity wave drag (NCGWD) due to parameterized GWD with a quasi-10-day periodicity, and 2) resolved GWs with quasi-10-day periodicity, specifically those with higher zonal wavenumbers (s>=20, shorter wavelengths). Our investigation revealed that both NCGWD due to parameterized GWD with a quasi-10-day periodicity and EPD generated by resolved GWs with quasi-10-day periodicity are relatively weak. Therefore, we infer that the Q10DW are likely generated in-situ due to the large-scale instability rather than being a result of GWD. To further clarify, we have added the following sentence to lines 533~535 in revised manuscript:" … In addition, Forbes and Zhang (2015) suggested that the dissipation of gravity waves filtered by the Q10DW wind field can generate a secondary Q10DW by momentum deposition. In this regard, the both parameterized GWs and resolved GWs…"

Q12. l. 483 "February and November"

Which year?

A12: As shown in Fig. S2, we found that in all yeas except 2014, the amplitude of Q10DW in EXP60 is stronger than in EXP75 during the February and November. Thus, the reference to "February and November" in our manuscript is not meant to indicate a specific year but rather a consistent pattern revealed in multiple years. To avoid any confusion, we will modify the sentence to "This section compares the Q10Dos around the mesospheric instability regions in the two SD-WACCM simulations (EXP75 and EXP60) during February and November across multiple years."

Q13. l. 484 "February and November are chosen because ..."

The justification is weak. It would make more sense to select the events that are examined in Figure 4,

where the Q10DWs are not only substantial in amplitude but also in qualitative agreement with observations.

A13: We conducted the analysis of all February and November cases as indicated by the yellow shaded date in Fig. S2. This analysis revealed that the wave activity of Q10DW in EXP60 is consistently more pronounced compared to EXP75 across all cases as shown in Figure R3. In the manuscript, we specifically chose to highlight cases of 5 February 2013 and 16 November 2016, as examples. To support our analysis, we will also include Figure S4 in the supplementary, which is similar to Figure R3.

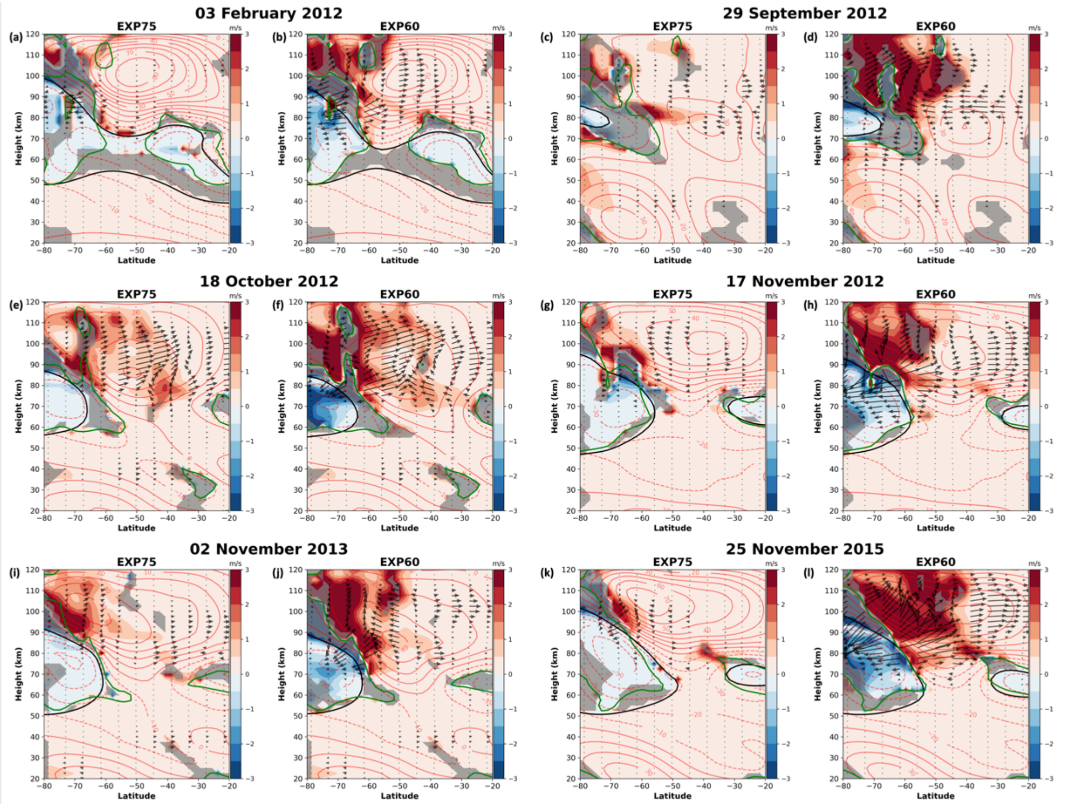

Figure R3. EP flux parallel to local group velocity $[\mathbf{F}/\mathbf{sgn}(\mathbf{A})]$ and normalized wave activity density [$\boldsymbol{A}$ $(\boldsymbol{\rho_0 a}\cos\boldsymbol{\phi})^{-1}$ given in the unit of m s^{-1}] for the Q10DWs on (a and b) 3 February 2012, (c and d) 29 September 2012, (e and f) 18 October 2012, (g and h) 17 November 2012, (I and j) 2 November 2013, and (k and l) 25 November 2015. The first and third columns and second and forth columns represent the results from EXP75 and EXP60, respectively. The activity density $\boldsymbol{A}$ is shaded in blue and red depending on its sign. The boundaries of the instability regions ($\overline{\boldsymbol{q}}_{\boldsymbol{\phi}} = \mathbf{0}$, green lines), the negative $\boldsymbol{n}^{\mathbf{2}}$ regions (grey shading), and the red contours for zonal-mean zonal wind are overplotted. For eastward (westward) zonal-mean zonal wind, contours are plotted in solid (dashed) lines, and contour interval is 10 m s^{-1}.

Q14. Summary

I do not see the merit of listing items here (#1-#6). #2 and #5 are not the description of results but the description of what the authors did to get the results.

A14: Thank you for your comment regarding the structure of the summary section. In response, we revised the summary to adopt a narrative style. This approach will ensure a more integrated presentation of both our methodologies and results.

References:

Forbes, J. M. and Zhang, X.: Quasi-10-day wave in the atmosphere, J. Geophys. Res.-Atmos., 120, 11,079–11,089, https://doi.org/10.1002/2015jd023327, 2015.

Rüfenacht, R., Baumgarten, G., Hildebrand, J., Schranz, F., Matthias, V., Stober, G., Lübken, F.-J., and Kämpfer, N.: Intercomparison of middle-atmospheric wind in observations and models, Atmos. Meas. Tech., 11, 1971–1987, https://doi.org/10.5194/amt-11-1971-2018, 2018.

Qin, Y., Gu, S. Y., Dou, X., Teng, C. K. M., Yang, Z., and Sun, R.: Southern Hemisphere Response to the Secondary Planetary Waves Generated During the Arctic Sudden Stratospheric Final Warmings: Influence of the Quasi-Biennial Oscillation, J. Geophys. Res.-Atmos., 127(24), e2022JD037730, https://doi.org/10.1029/2022JD037730

Yamazaki, Y. and Matthias, V.: Large-amplitude quasi-10-day waves in the middle atmosphere during final warmings, J. Geophys. Res.-Atmos., 124, 9874–9892, https://doi.org/10.1029/2019jd030634, 2019.

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