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Interactive comment on "Relation Between the Interannual Variability in the Stratospheric Rossby Wave Forcing and Zonal Mean Fields Suggesting an Interhemispheric Link in the Stratosphere" *by* Yuki Matsushita et al.

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Response to the comments from Reviewer #1

We greatly appreciate the reviewer for his/her critical reading and constructive comments. We have revised our manuscript as much as possible following his/her comments. Our response to each comment is described as follows:

Response to major comments:

1) *Why were 3-month averages used in the analysis? If shorter periods, such as individual months, were used, there would be a larger set of cases for investigating correlations. Did the authors probe the data to see whether correlation signals were stronger or weaker for averages over a subset of a season?*

We have added an explanation on the choice of the averaged period in Sect. 2, as follows:

"We analysed JJA-averaged fields to reduce the transient feature. We confirmed that the result for each month is qualitatively similar to those for JJA-averaged fields."

Significant correlation in the summer hemisphere is also observed for individual months although the correlation coefficient is small compared to that of JJA-averaged fields.

There is only a limited discussion of mechanism and I was unable to determine exactly what your interpretation is. The downward control mechanism that you refer to is valid for steady state (your three-month averages should be sufficient to satisfy this) but does not give a circulation that extends very far away from the region of the forcing (see any of the steady state figures in Haynes et al 1991). It is plausible that a dynamical mechanism would have a timescale shorter than the season-spanning three-month period and still affect the season-average circulation. It seems that you do not support this interpretation since you say (l. 170-171) that the pattern you see is not a result of the same processes that cause SSW.

We have revised Sect. 1 and Sect. 3. In Figure 2b, the interannual variability of the wave forcing averaged over Region A ($[\nabla \cdot F]_A$) is significantly correlated with the Rossby wave forcing around a 40 km altitude in the latitude range of 15°–70°S. It is indicated that the wave forcing in the subtropical region around 40 km shows similar interannual variability to that of $[\nabla \cdot F]_A$. Thus, the significant correlation of $\bar{v}^*$ observed in the region from the extratropics to subtropics of the SH can be explained by the local balance between $-f\bar{v}^*$ (Coriolis force) and the Rossby wave forcing. Around the equator, on the other hand, meridional circulation can be maintained without wave forcing. An explanation has been added in the 1st paragraph of Section 1:

"However, the Rossby wave forcing in the winter extratropics does not directly drive the cross-equatorial flow around the equator since the wave forcing cannot be balanced with Coriolis force associated with meridional wind owing to small f. Although the meridional circulation in the extratropics requires wave forcing to cross angular momentum $(\bar{M})$ contours aligned nearly vertically, the meridional circulation can exist around the equator without wave forcing because the $\bar{M}$ contours are horizontally aligned."

Since your analysis is limited to a single season, separated by nine months that are ignored, timescales of up to one year would be consistent with the results. Is external forcing responsible? You show that solar cycle forcing, which had been proposed in earlier studies, is not consistent with their results. Another "external" variation with a long timescale is the QBO; this can have an impact on circulation in the low latitude stratosphere. Looking at periods covering subsets of the three-month average would give some information about whether the signal has a timescale shorter than a year.

Following the reviewer's suggestion, we have newly performed the analyses focusing on the relation of our results with the QBO. We used $\bar{u}$ at the equator and 30 hPa as a proxy of the QBO phase and made a new plot showing the correlation of the QBO phase and the wave forcing (Figure 8 in the revised manuscript). The correlation between $[\nabla \cdot F]_A$ and $\bar{u}$ at the equator and at 30 hPa is small and is not significant (-0.14). Since the reason why the correlation between the QBO and the wave forcing in Region A is insignificant is out of the scope of this study, we only note here that the height region for the wave forcing in the present study (namely, Region A) is located at a much higher altitude than that were focused in the previous studies (e.g., Baldwin and Dunkerton, 1998; Salby et al., 2011). We have

added a figure (Figure 8) and a paragraph on this point to Sect. 4.2.

2) *Related to the above, the definition of winter as June, July, August appears arbitrary. Wave forcing in the southern winter is spread over a long period from May to November or December. Why were these months chosen?*

We have added an explanation on the choice of the analysed period in Sect. 2, as mentioned before. We have also added a paragraph in Sect. 4.3 on the results for the extended period from May to November. Although the results for the extended time period in the winter SH are largely similar to those for JJA, the correlation coefficients become weak, especially in the summer NH, and the latitudinal extents of the statistically significant response of $\bar{u}$, $\bar{T}$, and $\bar{v}^*$ are limited up to the equator.

3) *The statement (l. 26-27) that "the Rossby wave forcing in the winter extratropics cannot directly drive the cross-equatorial flow" needs more explanation since the results suggest to me that the Rossby wave forcing is driving the flow. Do you mean that this can only happen in certain circumstances that depend on the presence of an angular momentum gradient? Since there will generally be a region in the tropics where the gradient of M disappears, you seem to be implying that this wave driven circulation is not possible. Also, the statement later on (l. 142) seems to be saying something quite different: that the Rossby wave forcing is necessary to drive a circulation if there is an angular momentum gradient but a flow can exist without wave forcing if there is no angular momentum gradient. Please clarify.*

We use the phrase "directly drive" in the sense that the Rossby wave forcing is balanced with the Coriolis force for meridional wind to maintain $\bar{v}^*$. The phrase "cross-equatorial flow" means the meridional flow at low latitudes which crosses the equator, and does not mean the whole circulation from the equator to polar latitudes. We have revised the sentence (ll. 26–27 in the original manuscript) to clarify the meaning, as follows:

"the Rossby wave forcing in the winter extratropics does not directly drive the cross-equatorial flow around the equator since the wave forcing cannot be balanced with the Coriolis force for the meridional wind."

Likewise, I found support lacking for your conclusion that "The cross-equatorial residual mean flow is not directly driven by the Rossby wave forcing but indirectly maintained by the weak and small meridional gradient of the absolute angular momentum around the equator." Isn't it possible that the wave activity in the winter hemisphere, and the circulation response to it, is affecting M? Could you find cases where the wave forcing is high but M is large and vice versa? Otherwise, the relative impacts of these two processes cannot be separated.

We have cited Semeniuk and Shepherd (2002) and added a paragraph to Sect. 3. They examined the middle-atmosphere Hadley circulation and its interaction with extratropical wave-driven circulation, using a numerical model. They showed that the extratropical wave-driven circulation affects the meridional gradient of angular momentum ($\bar{M}_y$) around the equator together with the middle-atmosphere Hadley circulation, and that the significant overturning of $\bar{M}$ contours around the equator is attributable to the combination of the middle-atmosphere Hadley circulation and the extratropical wave-driven circulation. We have also added the results of the analyses on the $\bar{M}_y$ around the equator to Sect. 3. The correlation of $[\nabla \cdot F]_A$ with the $\bar{M}$ averaged over the region of the cross-equatorial flow (10°S–10°N, 35–45 km) is significantly positive (0.49). The wave forcing in the Region A is likely to drive the residual mean flow in the extratropics and subtropics of the SH and to modify the mean zonal wind around the equator with a small $\left|\bar{M}_y\right|$, and the present study does not intend to separate these processes.

4) *It would be interesting to compare the opposite time of the year (northern winter) to determine whether a similar correlation exists then? Finding such a correlation would provide support that there is a physical mechanism rather than a chance correlation.*

We have added a paragraph in Sect. 4.3 and figures as Fig. 9 in the revised

manuscript regarding the results for the northern winter. It is indicated that the interhemispheric link and cross-equatorial flow in the boreal winter is associated with the wave forcing in the NH stratosphere as well, while the latitudinal extent to the summer hemisphere is limited compared to that in the austral winter. Due to significantly large amplitude of planetary waves in the NH winter, which sometimes causes the breakdown of the polar vortex, a linear relation is unlikely obtained between the wave forcing and mean fields in the NH winter.

Response to minor comments:

1) *Some more description of the analysis is needed in Section 2. It took me a while to figure out that, when you discuss standard deviation, you mean only the standard deviation of fields that have already been averaged for the three months. The analysis for the wave amplitude is not clear – did you average daily amplitudes or daily Z'?*

We have revised the sentence (l. 82 in the original manuscript) as follows: "Figure 1c shows the climatology of three-hourly values of the root mean square of the geopotential height deviation $(Z\prime)$ from the zonal mean obtained at every three hours "

2) *This sentence is not clear; Figure 1b does not show wave forcing. In fact, I wasn't sure what you are referring to in this entire paragraph. As far as I can tell, you have used the term "wave forcing" to mean something very specific (EP flux divergence in Area A) but it does not fit with the usage here.*

We have corrected the number of the figure in the sentence (l.104 in the original manuscript) from 1b to 1d.

3)*"This indicates that the wave forcing in the SH affects the mean fields in the low latitude region of the NH". Be careful here. Correlation does not mean causation. You need more evidence to say that one timeseries is affecting the other, rather than vice versa or both responding to some other forcing.*

We have revised the sentence as followings:

"This indicates that the wave forcing in the SH is related to the mean fields in the low latitude region of the NH"

References:

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