Response to Reviewer1

(Please note that the Reviewer's comments are in italicized font and our responses are in normal font)

General comments

The authors evaluate the upper tropospheric momentum budget for ERA-5 reanalysis, and CMIP6 historical and SSP585 simulations. The paper explores the magnitudes of the zonal mean state advection of absolute vorticity and the stationary waves throughout the year, and across longitudes. In wintertime, over the East Pacific, they find that under the SSP585 scenario, the stationary waves contribution strongly decreases, likely due to the future El Niño SST anomalies simulated in CMIP6 but not currently observed.

The paper is clearly written and structured, presents some useful analysis of reanalysis and model data, the methods generally seem appropriate, and the results support the conclusions.

Answer: Thank you for your critical reading of our manuscript. We have updated the manuscript as per your suggestions and provided a point-by-point response to your comments below.

Specific comments

Budget closure*: The ERA5 momentum budget shows a large summertime residual of similar magnitude to the eddy term. This is discussed in the text, but would it be possible to either compare closure against other studies using ERA5, or to look into the cause of this? For example, ERA5 does provide the 'mean eastward wind tendency due to parametrisations' on model levels, alongside code to interpolate this to pressure levels. Given the focus of the paper, this seems an important point to have some explanation for. Could it arise from sub-daily transient activity? How well does the budget close across the pressure level for JJA?*

Answer:

The large residual was of concern to us too, and in fact, its large magnitude during the summer is somewhat well known, as we discuss in the manuscript. Moreover, the residual is quite large during NH summer than NH winter, as also pointed out in previous work (please compare Figures 1f & 2f in Lin et al. [2008] and Figure 4a & 4b in Yang et al. [2013]). As we discuss in the manuscript, the usual suspect here is Convective Momentum Transport [CMT; Carr and Bretherton, 2001, Lin et al., 2008, Yang et al., 2013].

Further, the following excerpt from Yang et al. [2013] sheds some more light on the issue at hand, "It should also be mentioned here that the estimated CMT is quantitatively only able to account less than half of the whole residual term even over the oceans, reflecting either the crudeness of the representation of the cloud detrainment rate by the precipitation rate or the contamination of X by other sources (e.g., gravity wave activities and errors of data itself)."

Indeed, our usage of daily averaged data underestimates the fluxes slightly. On repeating the exercise using 6-hourly data at a finer horizontal resolution of 1°, the peak fluxes during the monsoon are slightly higher than our original result (compare Figure 1 below with Figure 1 in the main document). However, the residual obtained in this exercise is similar to what we obtain using daily-averaged data at 2.5°.

Repeating the exercise using daily averaged ERA-Interim data at 2.5° gave a much smaller residual (Figure 1). This suggests that the relatively larger residual is possibly an ERA5 artifact. Per your

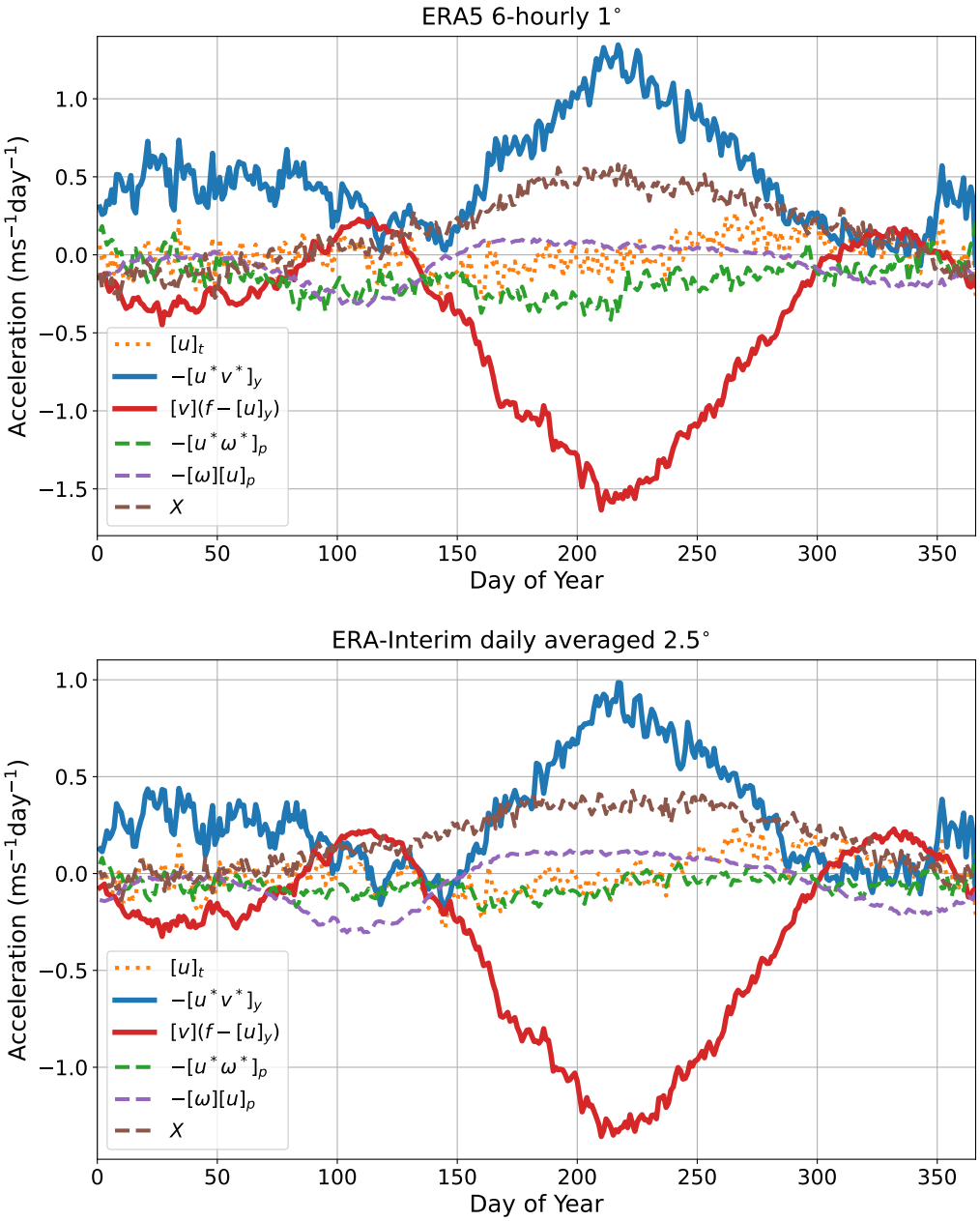

Figure 1: (top) Same as Figure 1 of the manuscript except for six hourly ERA5 data at 1° horizontal resolution. (bottom) Same as Figure 1 of the manuscript except for daily averaged ERA-Interim data at 2.5° horizontal resolution.

suggestions, the vertical profile of the budget terms (Figure 2) also suggests that the residual is small compared to other terms.

In this context, we have added the following to the text. "Indeed, the use of daily averaged wind fields underestimates the eddy covariances; however, the same calculation using the ERA-Interim dataset resulted in a relatively smaller residual (not shown), indicating that the large residual here may be an ERA5 artifact."

Given that the results and discussion in the manuscript surround the eddy and mean fluxes, we feel that further discussion of the residual may be beyond the scope of the present work but merits a separate investigation.

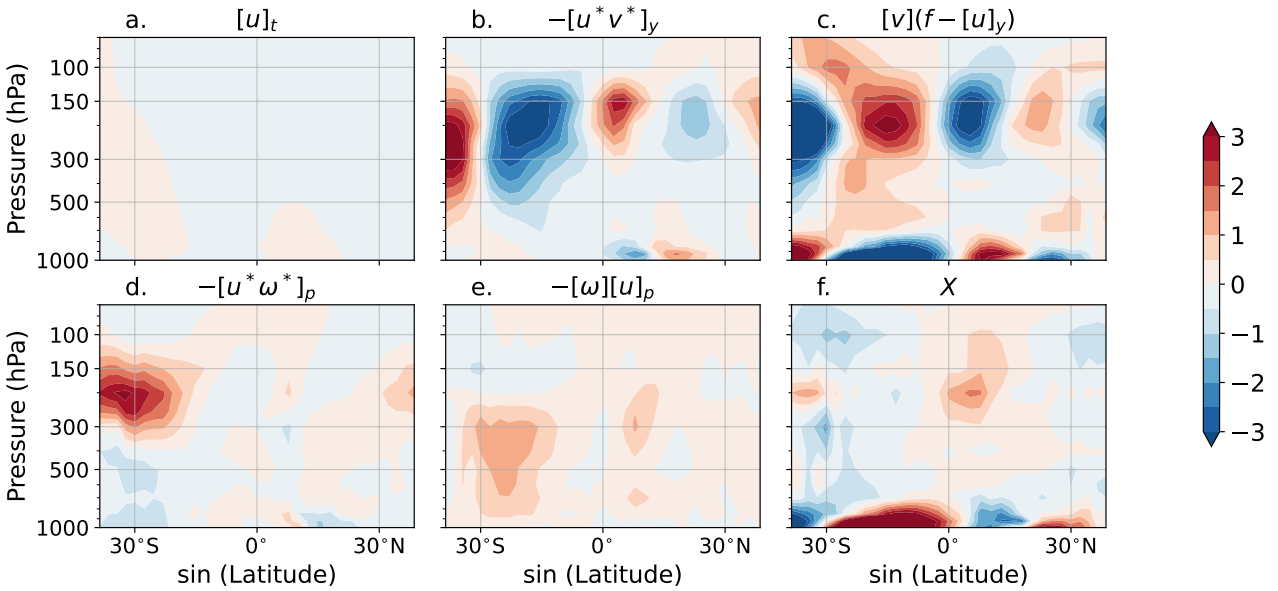

Figure 2: Climatological latitude-pressure profile of all terms in the zonal mean zonal momentum budget averaged over JJA.

***Novelty**: The paper is well-contextualized in terms of the previous literature, and I believe presents some new and interesting results. The authors highlight that changes in the regional eddy fluxes have not received much attention. However, it would be helpful to promote more clearly in the abstract, introduction and conclusions the key new findings in this study, perhaps simply by rephrasing from the passive to active voice: 'we find'.*

Answer: Thank you. To promote our new findings, we have made changes to the voice in the Abstract, Introduction, and Conclusions.

***CMIP6 simulations**: r1i1p1f1 is not the main simulation for some centres, and its meaning is not standard across centres. It may be possible to expand the number of modules used, although the 23 selected seem to cover a reasonable range of modelling centres.*

Answer: We chose *r1i1p1f1* because there was no reason for us to explicitly prefer any other variant-id. In fact, in an earlier analysis (https://arxiv.org/abs/2107.09646), we used *piControl* and *1pctCO2* and obtained similar results.

Methods

Which pressure levels are used in the CMIP6 data, do these match the ERA5 levels used?

Answer: We have now included these details in the Data section.

wap is not listed in the CMIP6 table, were vertical fluxes not evaluated for CMIP6?

Answer: No, vertical fluxes were not calculated for CMIP6 dataset. Using ERA5 reanalysis, we identified that the horizontal mean and eddy fluxes are the largest contributors to the zonal mean balance of momentum. In the context of climate change, we evaluate the changes to these horizontal fluxes. This approach streamlined and simplified our analysis significantly.

The acronyms (ua, va, tos, etc.) for the CMIP6 variables given in the table are not explained

Answer: We have added the variable descriptions in the Data section.

In section 2.1.3 it would be useful to note that the simulation includes a stationary wave SST, and to refer to the supplementary information, rather than relying on knowledge of the paper referenced.

Answer: We have added the description. We have also brought the relevant figure from the Supplementary into the main document (see Figure 11).

Calculating the fluxes from daily means appears to give reasonable results. It could be noted that this excludes any short-lived, subdaily activities.

Answer: We have added the note in the text.

Fig 2/averaging regions: I initially found the averaging regions described in the text hard to interpret, vertical lines on Fig 2 could make these clearer.

Answer: We have updated the Figure accordingly.

Line 283: "A possible reason for these discrepancies is that the model fluxes tend to be slightly displaced than those for present-day reanalysis." Not clear to me what is meant here, is this referring to spatial displacement, and in what sense?

Answer: Yes, we agree that the sentence creates more confusion than it brings clarity. We have removed that sentence.

Line 308: First sentence here refers to Fig 6, should note that this is discussing summer.

Answer: Corrected.

Fig 10: There is a shift to look at the Northern Hemisphere only here, is there a reason for this?

Answer: Yes. This is following the discussion in Section 4.2. As can be seen by comparing Figures 9b and d, the lower stratospheric eddy fluxes are strengthened over the Asia-Africa region. We hypothesized that this is due to the increased subtropical mass flux into the stratosphere during the NH summer, plausibly from the Indian summer monsoon flow. Further, the Asian summer anticyclone plays a vital role in the breaking of Rossby waves in the vicinity of the subtropical tropopause [Postel and Hitchmann, 1999]; structural changes induced by warming may influence the frequency and intensity of such events as well as stratosphere-troposphere tracer and mass exchange [Chen, 1995, Dunkerton, 1995].

Line 386: "Quite clearly, comparing the balance for the two scenarios suggests a higher degree of compensation between the beta and stretching terms via a larger divergence in the forced ensemble than the control set." This is not clear to me from Fig 10, the residual between the two terms may need to be shown to support this.

Answer: We have added the full vorticity budget [Eq 4 in the manuscript Sardeshmukh and Held, 1984] in the Supplementary.

Fig. 11: Not fully clear what is shown here. Do a and b show a vertical slice of the horizontal streamfunction, or a lat-pressure streamfunction?

Answer: Yes, the Figure shows a vertical slice of the horizontal streamfunction.

Fig. 12 caption: it needs to be made clear in the caption that quivers show differences in left column but absolute values in right column.

Answer: We have added that note in the Figure caption.

Fig. 13 caption: please could you specify that positive values correspond to northward fluxes in both panels, to make this simpler to interpret.

Answer: We have added that note in the Figure caption.

Line 446: It would be helpful to note the longitudes to look at for the westerly duct here, particularly given the change in longitude axis from -180-180 to 0-360.

Answer: We have marked out the longitudes to look for with a box.

Line 534-535: I found this sentence confusing. To me, "captured faithfully" implies models are consistent with the observations, but the sentence continues to say they are not. Is the intention to say that models consistently show this behavior?

Answer: We have removed the word "faithfully"

Line 544-545: "Indeed, there is a fair spread amongst the models; some models in the ensemble indicate a switch with equatorial superrotation as an outcome of climate change" From Fig 14 I can't see any that go from -ve in the control to +ve in the forced, as seems implied by this sentence.

Answer: We have changed the sentence.

Technical corrections

Equations 1 & 3 use x and y and lambda and phi respectively. Similarly deviations from the zonal mean are denoted by asterisks and primes differently in these equations. It would be good to make these consistent.

Answer: Corrected.

Section 2.2.3: should F by F_s in the sentence discussing WKB theory?

Answer: Yes. Corrected.

Line 225: "While the wave activity flux in (arrows in Figure 4b) captures stationary contributions" Delete 'in'

Answer: Corrected.

Line 339: missing &

Answer: Corrected.

Fig. 5: Please add a legend to avoid readers scrolling to check Fig. 3.

Answer: Figure updated, as suggested.

Fig. 9: Could the same colorbar be used for both columns?

Answer: Yes.

References

Matthew T Carr and Christopher S Bretherton. Convective momentum transport over the tropical pacific: Budget estimates. *Journal of the atmospheric sciences*, 58(13):1673–1693, 2001.

P Chen. Isentropic cross-tropopause mass exchange in the extratropics. *Journal of Geophysical Research*, 100:16661–16673, 1995. doi: 10.1029/95JD01264.

TJ Dunkerton. Evidence of meridional motion in the summer lower stratosphere adjacent to monsoon regions. *Journal of Geophysical Research*, 100:16675–16688, 1995. doi: 10.1029/95JD01263.

Jia-Lin Lin, Brian E Mapes, and Weiqing Han. What are the sources of mechanical damping in matsuno–gill-type models? *Journal of Climate*, 21(2):165–179, 2008. doi: 10.1175/2007JCLI1546.1.

GA Postel and MH Hitchmann. A climatology of rossby wave breaking along the subtropical tropopause. *Journal of the Atmospheric Sciences*, 56:359–373, 1999. doi: 10.1175/1520-0469(1999)056<0359:ACORWB>2.0.CO;2.

Prashant D Sardeshmukh and Isaac M Held. The vorticity balance in the tropical upper troposphere of a general circulation model. *Journal of Atmospheric Sciences*, 41(5):768–778, 1984. doi: 10.1175/1520-0469(1984)041<3C0768:TVBITT>2.0.CO;2.

Wenchang Yang, Richard Seager, and Mark A Cane. Zonal momentum balance in the tropical atmospheric circulation during the global monsoon mature months. *Journal of the atmospheric sciences*, 70(2):583–599, 2013.