Response to Reviewer 2

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

*** Summary**

The authors diagnose the zonally resolved zonal momentum budget for the tropics in reanalysis data and CMIP models, both control and SSP8.5-forced. They split out the contributions from many different terms, including the rotational and divergent components.

The writing is for the most part clear, and the Introduction sets up a potentially compelling story. But—and this might just be me—I struggled to keep focus/interest once the manuscript got into its results. The first few figures, there were already a number of things regarding their interpretation that were tripping me up, as noted below. So it was then hard to then make much of the remainder of the results.

That said, I don't see any glaring errors in the analyses, and the results presented are worthwhile contributions to the literature pending some cleaning up as detailed below.

Thank you for the comments on our manuscript. We hope that the revision makes the presentation a little clearer and keeps the reader engaged through the manuscript.

*** Major Comments**

**** Residual term and daily data** *In your Fig. 1, in NH summer the leading balance is not, as you state, a two-term balance between the eddy momentum flux divergence and mean meridional advection...it's a three-term balance of those and the residual. In your discussion of this issue, you don't bring up what to me seems like a likely contributor: your use of daily averaged data. The standard is to use 6-hourly (or 3-hourly) covariances of instantaneous fields.*

I'm not necessarily saying you need to re-do the whole thing with hourly data, as that's a heavy lift indeed. But it would make everything much more compelling, and ERA5 hourly data is available to make this possible.

Answer:

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°.

Further, repeating the exercise using ERA-Interim using daily averaged data at 2.5° gave a much smaller residual (Figure 1). This suggests that the larger residual is possibly an ERA5 artifact. Per your suggestion, we have repeated the calculation using 3-hourly 0.25° resolution ERA5 data (Figure 2); however, the results are largely similar to the one we have presented in the manuscript and not much different from that calculated using coarser 1° 6-hourly data.

We would like to add that the residual is quite large during NH summer than NH winter, as 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].

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)."

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."

**** Stationary vs. transient eddies**

The framing is in terms of the mean meridional circulation on the one hand versus all eddies on the other hand. But stationary eddies and transient eddies are very different from one another, and you argue that one or the other plays more important roles in different locations and contexts. So I'm wondering if it's worth the effort to explicitly disentangle them, presenting results for both individual eddy terms.

Answer:

We had considered this partition. Our objective was to highlight the contrasting nature of the eddies in the tropical momentum balance – that both tropical and extratropical modes are involved in the balance rather than just tropical modes. We found that this was most succinctly captured by partitioning the tropics and then using the rotational-divergent partition. We felt it would be difficult to establish the involvement of tropical and extratropical modes using the stationary/transient partition because both tropical and extratropical modes are composed of stationary and transient components.

As you can see in Figure 3, the eddy momentum flux convergence by stationary eddies explains a large portion of the total eddy momentum flux – a fact that holds for the Asia-Africa region as well because the climatological stationary Rossby waves are prevalent there. However, the transient contribution is relatively small. In comparison, the eddy momentum flux convergence associated with the Af-A and CP-WA regions is much larger (compare with Figure 3a in the manuscript).

Further, there is a fairly large literature surrounding stationary and transient eddies [for example Dima et al., 2005, Zurita-Gotor, 2019]. However, to the best of our knowledge, the prominence of stationary Rossby waves in the Asia-Africa region versus the seasonally sensitive prominence of the extratropical waves in the East Pacific hasn't received much attention.

*** Minor comments**

- On superrotation, see also Zhang and Lutsko, doi.org/10.1175/JAS-D-22-0066.1

Answer: We have included the reference.

- On the SSP8.5 scenario, just be aware that it is now virtually certain to not occur: doi.org/10.1038/d41586-020-00177-3

Answer: Right, we have made a note in the text.

- Table 1 :: there's no need for the variable columns, since every single one is checked. Just list the

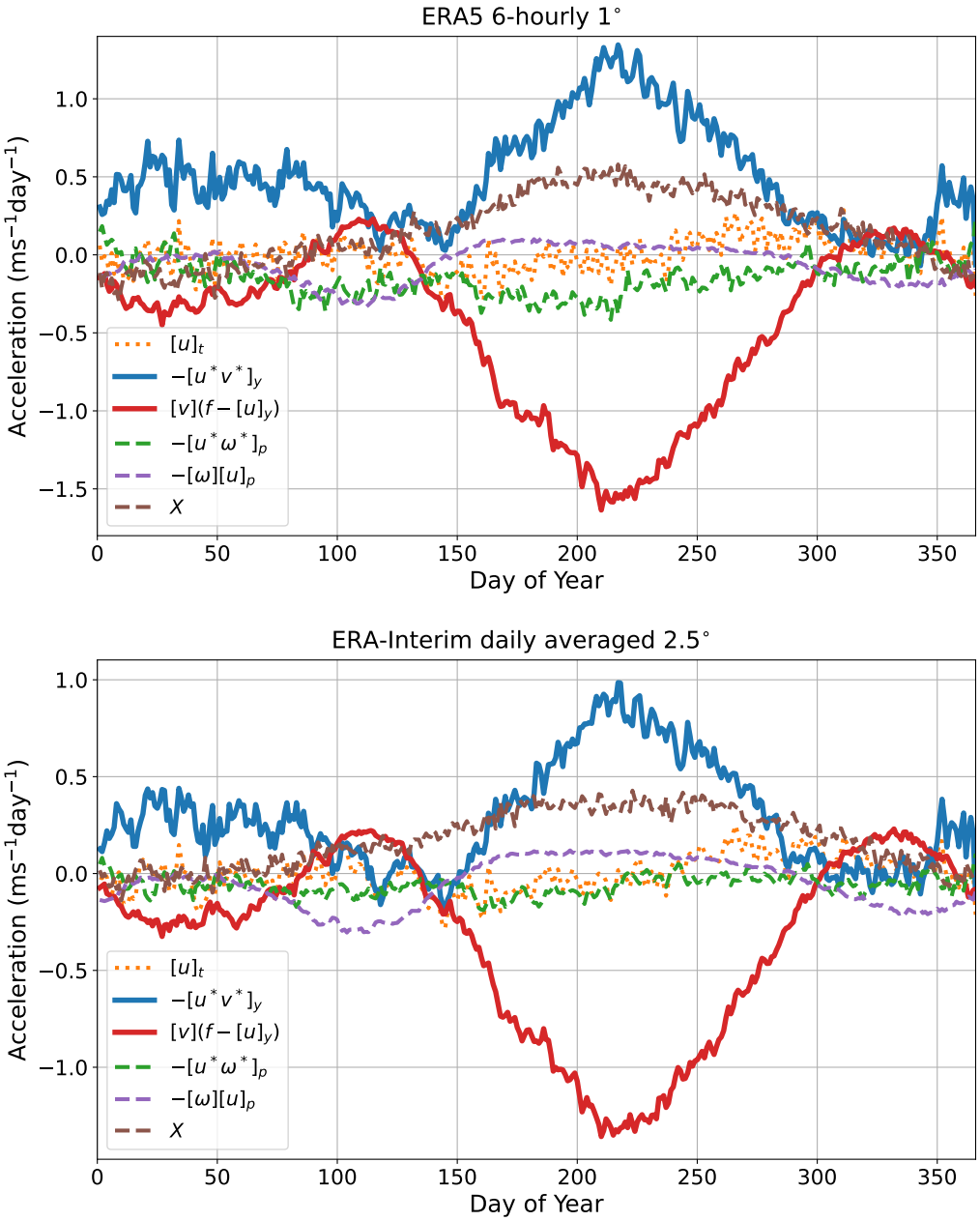

Figure 1: (top) Same as Figure 1 of the manuscript except for six hourly ERA5 data at 1° horizontal resolution. (bottom) Same as Figure 1 of the manuscript except for daily averaged ERA-Interim data at 2.5° horizontal resolution.

model names and note either in the caption or main text that they all include the five variables you've listed.

Answer: Corrected.

- Text after Eq. 3, the F term is missing the "s" subscript

Answer: Corrected.

- L147 :: if it's already been published and discussed, it's not "surprising"

Answer: Corrected.

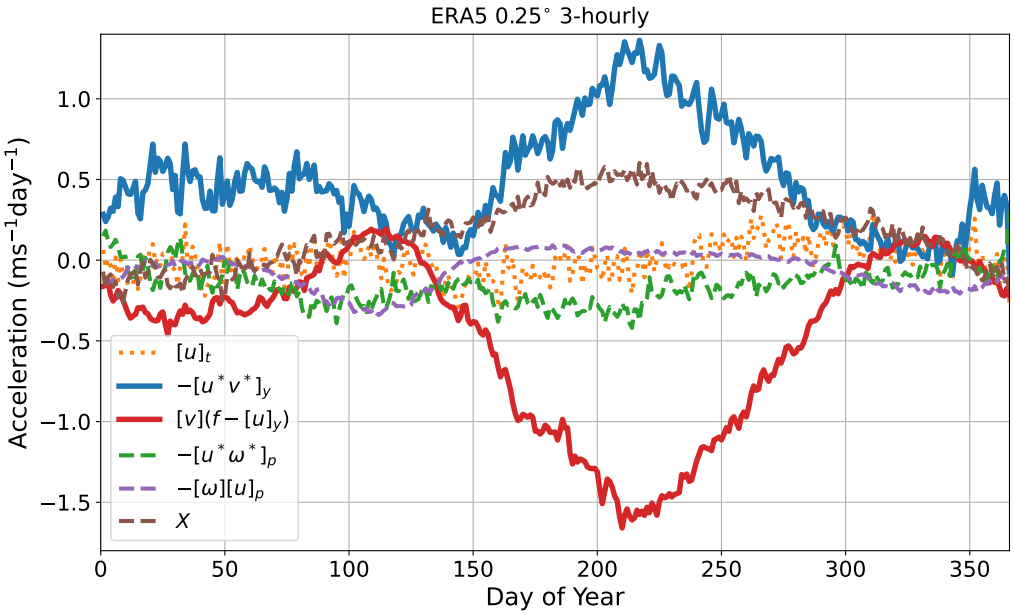

Figure 2: Same as Figure 1 of the manuscript except for three hourly ERA5 data at 0.25° horizontal resolution.

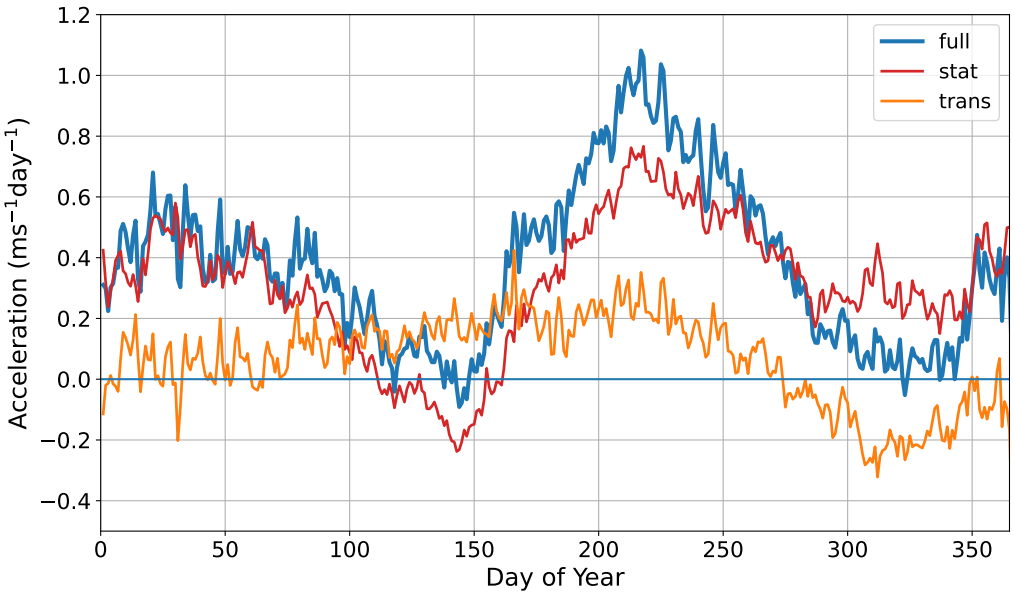

Figure 3: Partitioning of the full eddy momentum flux convergence (blue) into contributions by stationary (red) and transient (orange)) eddies. All quantities are averaged over the 150-300 mbar layer.

*- Fig. 3:: If you're saying the other components that aren't plotted are small, then why doesn't the total visually add up to the sum of the plotted ur*vd and ur*vr lines in a lot of places?*

Answer: Please refer to Figure 4 in this document. The terms $u_d v_d$ and $u_d v_r$ are much smaller than the other terms and are fairly constant throughout the year. We have added the following sentence in the main text

"Please note that the contribution from the $u_d^* v_d^*$ and $u_d^* v_r^*$ terms are much smaller than the other terms and are fairly constant throughout the year (not shown)."

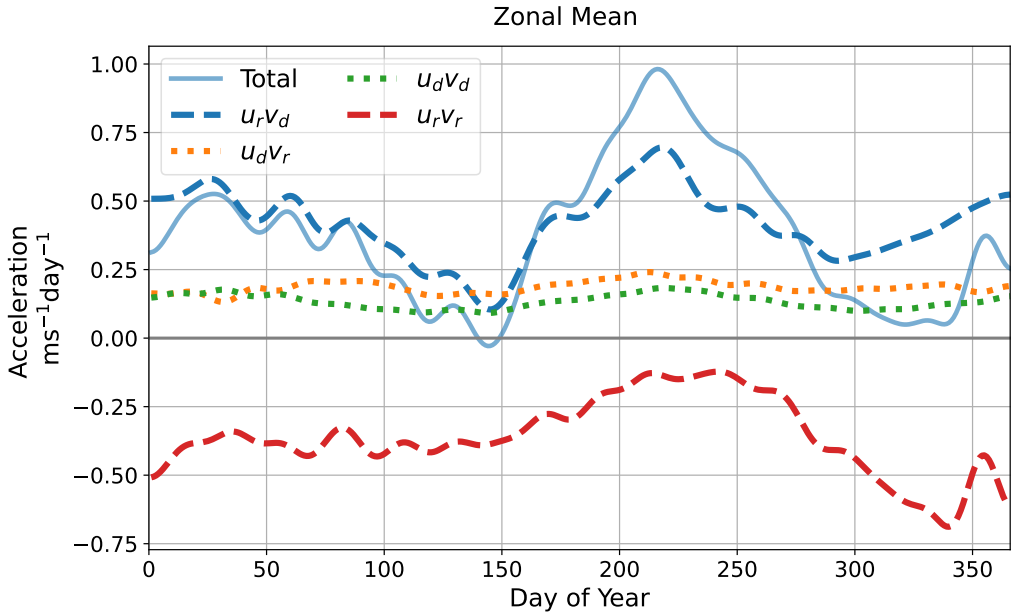

Figure 4: All components of the rotational divergent partition of the zonal mean eddy momentum flux convergence.

*- Fig. 3b :: the ur*vd legend label doesn't show up as dash-dotted, just as a shorter line than the total*

Answer: We have updated the Figure. The dash-dotted $u_r v_d$ line plots are now dashed.

- L259 :: "As long as ur-vd or tropical features dominate the eddy and mean fluxes, they should oppose each other in strength and symmetry" I don't understand this

Answer: We have removed the sentence.

- "tropical momentum balance is delicate" this is said a few times, but what does it really mean? Regarding the response to a forcing, the prevailing balance does not constrain the response in any way—a given forcing could operate primarily by a third term for example, so I don't follow e.g. L488-491.

Answer: Right. Warming-induced changes to the zonal momentum balance may affect the terms involved in different ways. We have restructured these bits for more clarity.

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.

Ioana M. Dima, John M. Wallace, and Ian Kraucunas. Tropical zonal momentum balance in the NCEP reanalyses. *Journal of the Atmospheric Sciences*, 62(7):2499–2513, jul 2005. doi: 10.1175/jas3486.1.

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