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Reply on RC3

Yetao Cen et al.

Author comment on "Suppressed migrating diurnal tides in the mesosphere and lower thermosphere region during El Niño in northern winter and its possible mechanism" by Yetao Cen et al., Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2021-884-AC3, 2022

Reviewer #2 (Comments to Author (shown to authors):

This manuscript investigated the migrating diurnal tidal variability in the mesosphere and lower thermosphere due to the El Niño-Southern Oscillation, and the driving mechanism of this variability. This is one of the important issues related to the interannual variability in the MLT region. The authors showed the significant negative correlation between the residual of diurnal tidal amplitude in the MLT and the Niño3.4 index, and attributed this diurnal tidal variability to its tropospheric source forcing change, background wind effect, and the modulation of the gravity wave drag. Although this paper included some interesting results, overall I think that the paper only has decent scientific progress since it is already well established of the negative correlation between the SOI/Niño3.4 index and the DW1 amplitude in the MLT region. The analysis is a good start point but I think the results presented herein are incomprehensive. Additional analysis with deeper informative results is needed to justify publication in ACP. I will indicate a major revision for this manuscript and think this manuscript can make an excellent contribution after major revision.

Data and method

1. The archived model data from latest WACCM 6 and SD-WACCM-X version 2.1 runs are both publicly available on CESM website, with significant change from previous version. The authors should provide reasons why they chose an older version of model output.

Response: Thanks for your suggestion. The latest version of WACCM (WACCM6) has been adopted to investigate the DW1 tide with different predictors, including ENSO by Ramesh et al. (2020). The MLT DW1 tidal T is suggested to be a significantly negative response to Niño 3.4, which is, however, opposite to the negative DW1-ENSO relationship suggested by SABER observations. The different DW1-ENSO relationship between different versions of WACCM simulation may be attributed to the changed scheme utilized in generating ENSO and QBO (ENSO and QBO are self-generated in WACCM6 simulated by Ramesh et al. (2020), while are nudged to MERRA2 below 50 km in the SD-WACCM4) and the associated atmospheric variation. As a result, the variation associated with tidal excitation or propagation may not follow reality.

As WACCM-X is built upon the chemistry, dynamics, and physics of CAM4 and WACCM4, the tidal forcing and the middle atmospheric variability in SD-WACCM-X follow that in SD-WACCM4 below the thermosphere. Thus, a similar response of MLT tide to ENSO should be expected. However, on the CESM website, there are neither parameterized tidal variables nor the averaged variables with a time resolution of less than one day in the datasets of SD-WACCM-X version 2.1. Both CAM and WACCM have seen their own significant recent developments, including increased horizontal resolution. While CAM6 and WACCM6 have been released as part of CESM 2, WACCM-X will incorporate the recent improvements in the lower and middle atmosphere components of CESM in the future versions. (Liu et al., 2018). Given the agreement with SABER observations and the availability of data, the simulation from SD-WACCM4 is adopted in this study to investigate the mechanism how ENSO could modulate the MLT DW1.

Tidal forcing

2. The author stated that the amplitude and phase of DW1 in the MLT could be potentially modulated by the ENSO and used a DW1 vector amplitude to combine their anomaly related to the Niño3.4 index. I think it will be better to assess the ENSO impact on the DW1 amplitude and phase separately.

Response: Thanks for your suggestion. Figure R1 shows the average DW1 temperature amplitude of SABER observation during 2002-2020 winter (Figure R1a) and the climatology average DJF DW1-T phase (Figure R1b). Figure R2 shows the SABER DW1-T amplitude and phase anomaly during El Niño winter. The amplitude of DW1 in the equatorial region is significantly reduced, while the phase anomaly is not obvious (less than 1 hour in most areas) during El Niño winter.

The discussion assesses the ENSO impact on the DW1 amplitude and phase separately has been discussed in lines 245-247 as "The amplitude of DW1 in the equatorial region is significantly reduced, however the phase anomaly is not drifted much (less than 1 hour) during El Niño winter. (figure S1, S2)" in the revised manuscript.

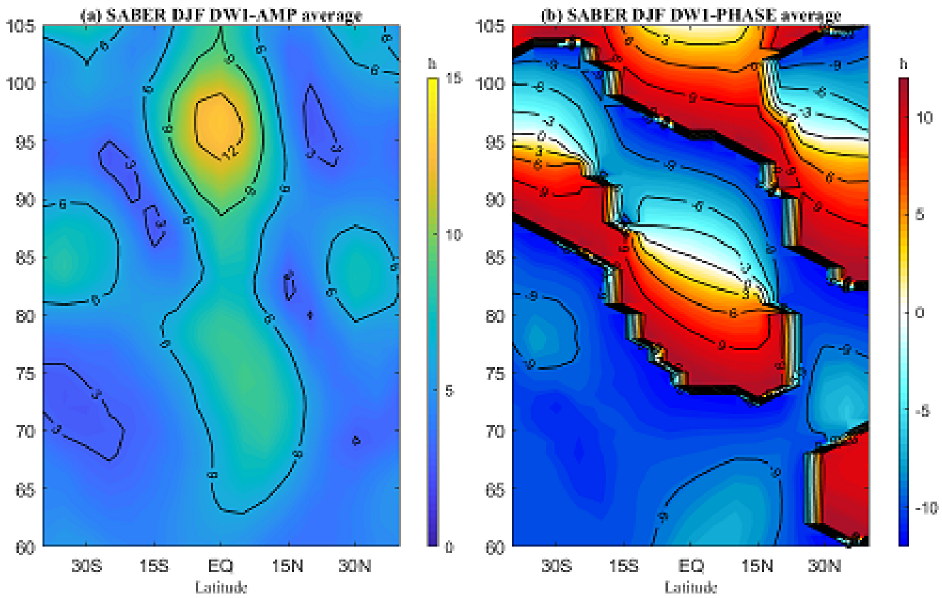

Figure R1 (Figure S1 in the revised supplement). (a) The average DW1 temperature amplitude of SABER observation during 2002-2020 winter (DJF, Dec-Jan-Feb). (b) the same as (a), but for phase.

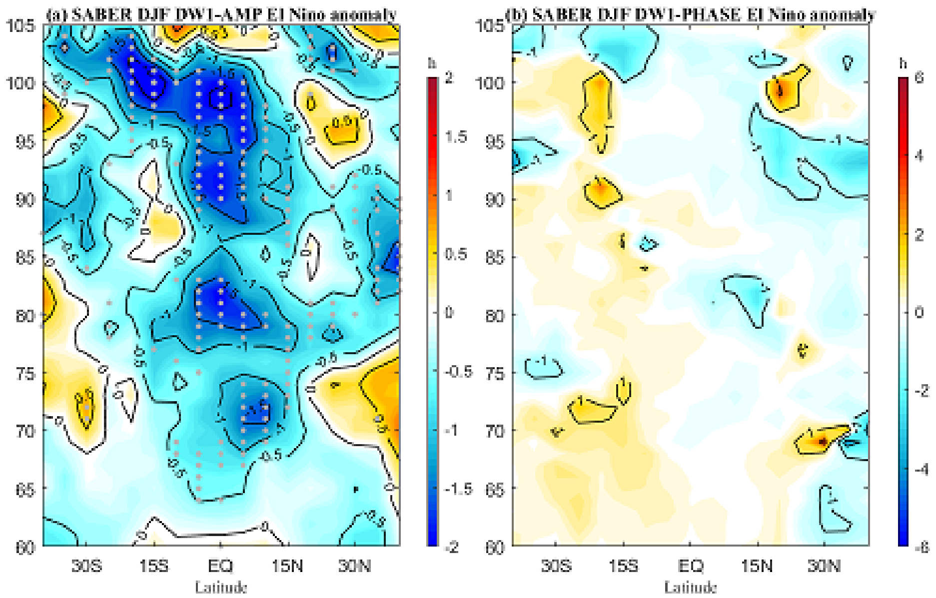

Figure R2 (Figure S2 in the revised supplement). Dec-Jan-Feb mean of the SABER DW1-T (a) amplitude and (b) phase anomaly during El Niño years. Stippling indicates statistical significance at the 95% level using Student's T test.

3. Do the authors have an explanation why the negative response becomes much weaker at the height of ~95 km in Figure 2A (even positive correlated in the Northern hemisphere low-latitude region)? SABER data has a great quality at this altitude and the DW1 amplitude roughly maximizes at the same region. I therefore think the result presented herein weakened the conclusion in the manuscript. Also, if the change of the tidal forcing due to the ENSO phase is the main driver of the DW1 anomaly in the MLT region, the negative response in the SABER DW1 is likely to be coherently equal in height.

Response: Thanks for the suggestion. As you mentioned, the DW1 response to ENSO over the equator is negative between 90-105 km but becomes weaker at 95 km. We think this attenuated negative DW1 response may be related to the dissipation or damping of the tide near 95 km. As a relative enhancement should account for a shorter vertical wavelength in the Rayleigh friction coefficient proportional (Forbes et al., 1989), the dissipation for tide should be enhanced as a result and vice versa. As presented in Table R1, the vertical wavelength of DW1 at 95 km is increased (while decreased at around 90 and 100 km), which would suppress the Rayleigh friction coefficient and lead to less tidal dissipation. Therefore, the suppressed tidal propagation into this area could be compensated by less dissipation, which together results in a relatively weak negative or even positive response at 95 km. According to previous research (Forbes et al. 1989), the enhancement of the zonal wind (observed by meteor radar at KT) will lead to an increase in the vertical wavelength. The zonal wind response to ENSO at 95km during 2002-2017 winter is positive observed by meteor radar at Koto Tabang (100.32°E, 0.2°S), which may result from less westward momentum from the dissipation of DW1. The interaction of gravity waves and tides may also play a role in modulating the tidal amplitude at different altitudes. However, the SD-WACCM simulation failed to perform a similar tidal response at 95 km. Further investigation with more detailed diurnal GW from observation or the improved gravitational wave parameterization scheme and higher vertical resolution in model simulation are need in the future work.

The discussion between these reasons has been added in lines 473-485 in the revised manuscript.

Table R1. Comparison of vertical wavelengths at different heights in climatological mean winters and El Niño winters.

Saber height	88-92 km	93-97 km	98-102 km
Climatological mean vertical wavelength (km)	20.8	25.2	20.2
El Niño year vertical wavelength (km)	18.5	26.6	18.2

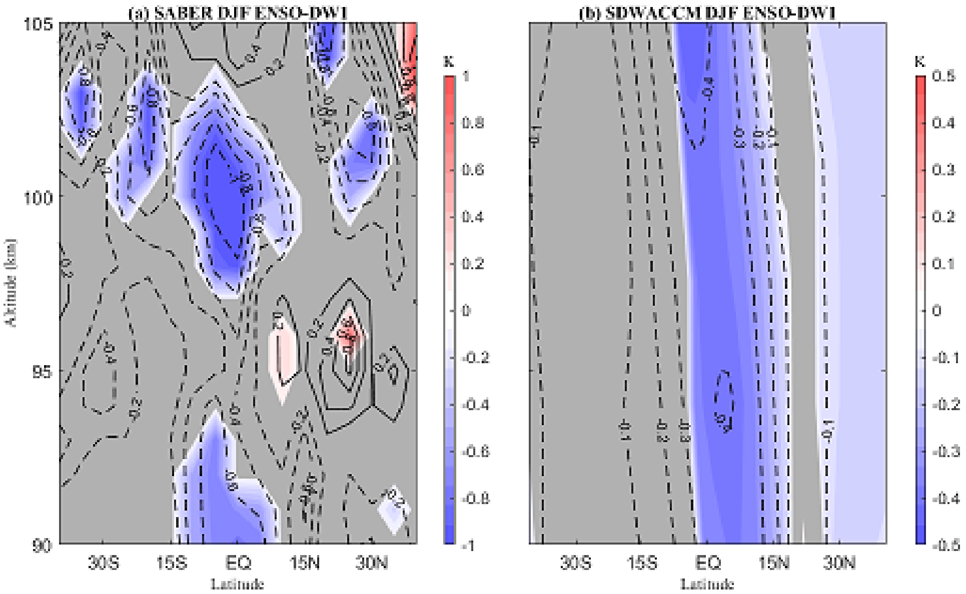

Figure R3 (Figure 2 in the original manuscript). The linear regression coefficient of normalized Niño3.4 in SABER (a) and SD-WACCM (b) winter DW1-T. The contour interval is 0.2 K for SABER and 0.1 K for SD-WACCM. Red represents a positive response, and blue represents a negative response; the grey regions denote confidence levels below 95% for the F test.

4. In Lines 314-315, the authors averaged the DW1 heating rate with identical altitude in Pedatella et al. 2013, and drew an opposite conclusion (negative correlation) with the previous paper (positive correlation). However, the DW1 heating rate between 5-10 km in Figure 4 is weakly positively correlated with the Niño3.4 index. This result seems not consistent with the text in Line 314-315. I hope the authors can provide some more explanation to support their statement.

Response: Thanks for your suggestion. Utilizing the Whole Atmosphere Community Climate Model (WACCM) version 4, Pedatella & Liu (2012 and 2013) suggested that El Niño could enhance the MLT DW1 tide during winters due to increased tropospheric radiative forcing. In their simulation, ENSO events are generated due to internal model dynamics, in which there is no quasi-biennial oscillation (QBO) events.

In the "Specified dynamics" version of WACCM4 (SD-WACCM), which is based on WACCM4 and nudged to meteorological fields from Modern-Era Retrospective Analysis for Research and Applications (MERRA) reanalysis data in the troposphere and stratosphere (from the surface up to 1 hPa) and then is freely run in the MLT (above 0.3 hPa) (Kunz et al., 2011). the atmospheric variables such as QBO are consistent with the reanalysis in the troposphere and stratosphere. The SST which follows the observation is prescribed in SD-WACCM. Both the SST and the dynamics in the lower atmosphere are different between SD-WACCM4 and WACCM4 utilized by Pedatella & Liu (2012 and 2013), which could result in the difference in HR response at the same region (e.g., 5-10 km) during ENSO events, in turn, may play a role in the opposite response of DW1 to ENSO in the two versions of WACCM.

Although the linear regression coefficient in HR is positive at 5-10km over the equator (5°N-5°S), the coefficients at 5-30°N(S) are negative (Figure R4), which is opposite of the equator (5°N-5°S). Pedatella et al. (2013) adopted the HR in the upper tropical troposphere (5-10 km within ±20°) to estimate the ENSO-induced variation in the DW1 tidal source. For the same region, the averaged HR is negative in SD-WACCM.

The discussion about the HR averaged over 5-10 km, 20°N-20°S (the same as in Pedatella et al., 2013) has been added in lines 335-340 in the revised manuscript.

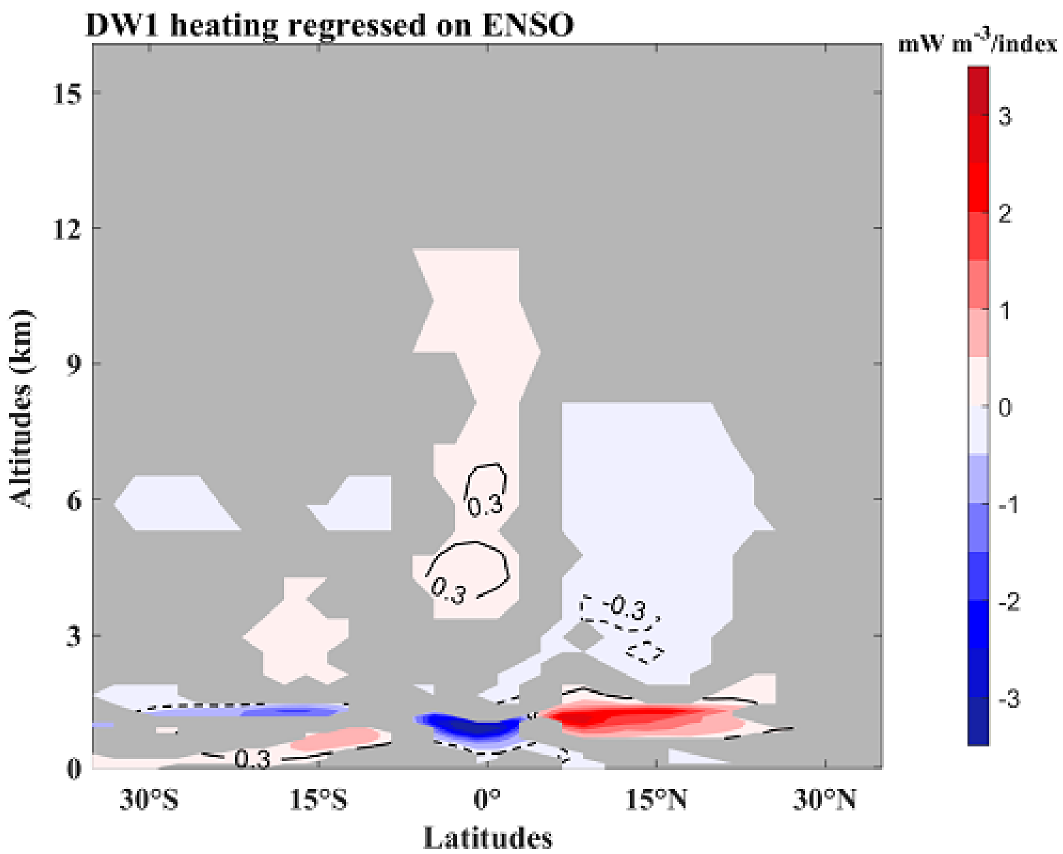

Figure R4 (Figure 5 in the revised manuscript). The linear regression coefficient of normalized Niño3.4 in SD-WACCM heating amplitude (mW/m^3 per index) during 1979-2013 winters (DJF). Red represents a positive response, and blue represents a negative response; the grey regions denote confidence levels below 95% according to the F test.

Effect of background wind

5. Figure 5: It seems to me that the result is not robust enough to be an independent section. My main concern is the statistical significance. The coefficient is small (the mean value of R in the MLT is roughly equal to one in McLandress, 2002, DOI:10.1029/2001GL014551) and the climatological value of R from the WACCM should be included in the manuscript, at least in the supplement. I also think the authors should perform the F-test and assess the statistical significance, similar to the tidal forcing section.

Response: We modified Figure R5 (Figure 6 in the revised manuscript) to show significant areas of the MLR coefficient of R on Niño 3.4. The green thick solid line represents the mean value of the equatorial ratio of the absolute and planetary vorticity R (15-30°N and 15-30°S), and the thick lines indicate the area where the regressed coefficients are significant. Below 60 km, the ratio R exhibits negative and positive responses to ENSO depending on different altitudes in the northern and southern subtropics (significant enhanced around 20-25 km and significant weakened near surface, at 35 km and 55km). The mean R value (15-30°N and 15-30°S) response to ENSO is significantly positive at 60-90 km, which would lead to the suppressed propagation of DW1 above these areas. Although R value is significant at 60-90 km, the coefficient of R is relatively small to the mean value of R, the impact of R on tidal propagation may play a secondary role in ENSO-DW1 connection.

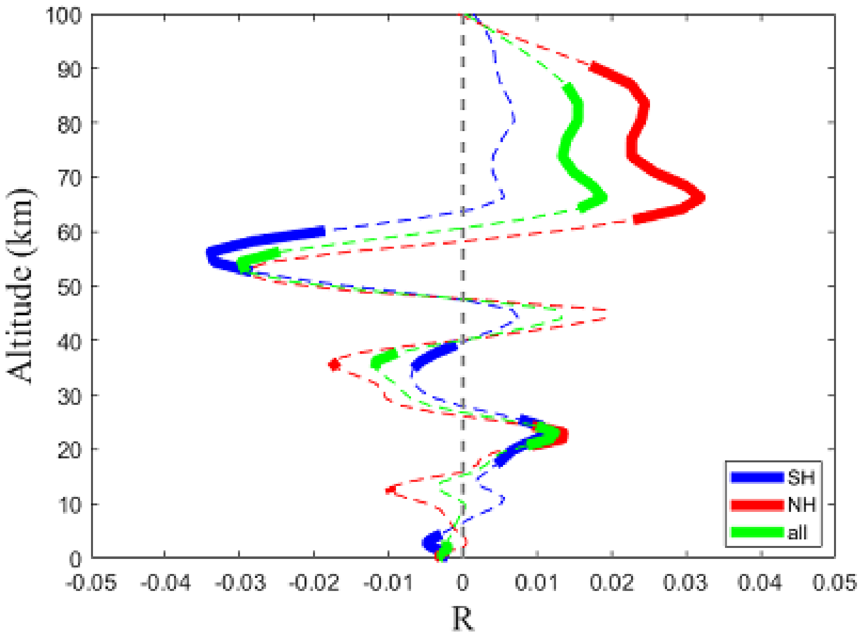

Figure R5 (Figure 6 in the revised manuscript). The anomaly of the ratio of the absolute and planetary vorticity, δR. The thin, dashed red, blue and green lines denote the averages of the Northern Hemisphere (from 15°N to 30°N), Southern Hemisphere (from 15°S to 30°S) and the whole (15-30°N and 15-30°S) , respectively. The thick, solid lines denote confidence levels below 95% for the F test.

6. Besides, it is hard to justify the change of R-value is the driver of the DW1 interannual variability; or the change of R is just related to the ENSO phase and has a similar trend as to the DW1 variability.

Response: Thanks for your suggestion. The relevant content is explained in lines 371-377 in the revised manuscript, the specific content is as follows: "The correlation coefficient between the R value and DW1 during the winter of 1979-2014 is -0.33 (significant at 95% level) in the SH, and is -0.37 (significant at 95% level) in the NH the correlation coefficient, both of which are significantly correlated. The significantly negative correlation between R and DW1 tide implies that the R plays a role in modulation the upward propagating of DW1 when no ENSO event occurs. The variation of R and DW1 should not be attributed to the impacts of ENSO separately.".

Effect of gravity wave drag

7. The authors can make a great contribution in this section with a thorough analysis. For example, is slow or fast waves to contribute most to the DW1 variability? Besides, do the authors have reasons not to mention the frontally generated GW impact on DW1 variability in the present manuscript? The zonal mean GW forcing due to the frontal systems in WACCM is about a order of magnitude stronger than that from the convective GWs (Richter et al., 2010, DOI:10.1175/2009JAS3112.1). Apparently, the authors should be able to identify the impact from two different GW sources on the DW1.

Response: Thanks for your suggestion. Although it is impossible to recognize the effect fast and slow gravity waves respectively due to lack of separate output of them of in SD-WACCM simulations, we think the fast wave should make a major contribution to tides as suggested by Fritts et al. (1989□2003). As you mentioned, the GW forcing due to the frontal systems in WACCM is about a order of magnitude stronger than that from the convective GWs. However, the GW is mainly induced by the convection in the tropics, while the GW is generated by the frontal systems in the middle to high latitudes (Figure R6). Figure R7 shows the response of GW to ENSO, and it can be seen that the GW drag anomaly at the tropics in El Niño winter is mainly caused by convection. The discussion between GW drag generated by frontal systems and convection has been added in lines 387-388 in the revised manuscript.

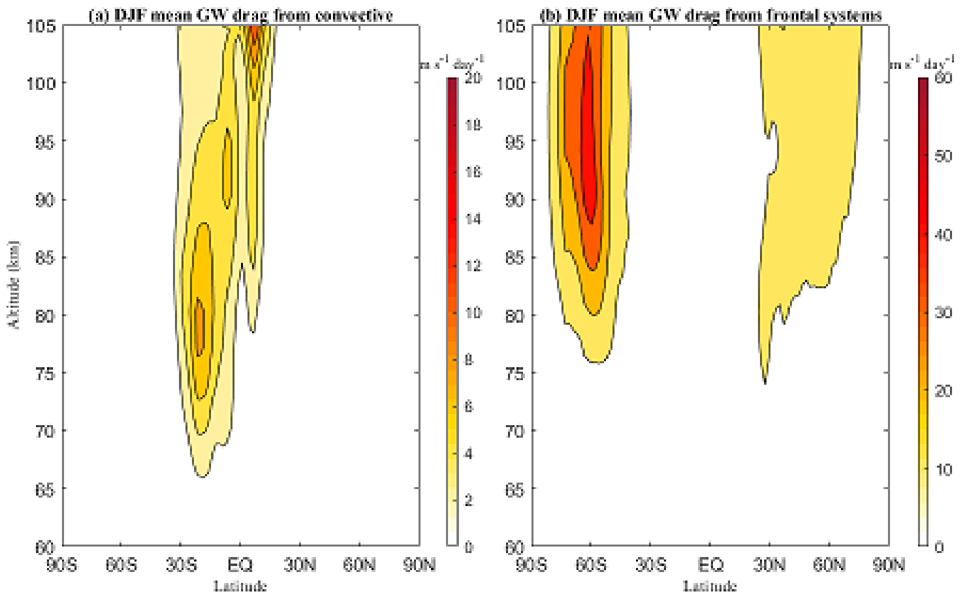

Figure R6 (Figure S5 in the revised supplement). The zonal mean GW drag average in winter due to convective (a) and the frontal systems (b) in SD-WACCM.

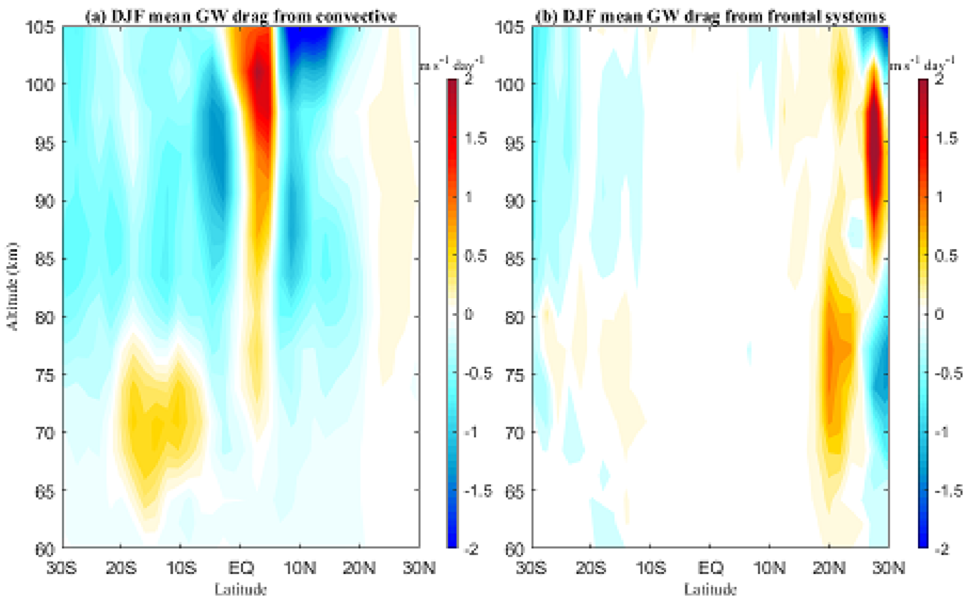

Figure R7 (Figure S6 in the revised supplement). The zonal mean GW drag anomaly during El Niño winter due to convective (a) and the frontal systems (b) in SD-WACCM.

8. I am a bit confused about the definition of the gravity wave "drag". Does this result imply the DW1 phase is modulated by the ENSO-related GW variation?

9. I also would like to suggest the authors may consider pulling Figure S3 and S4 into the main text and clarify the difference between GW forcing and drag, not just mathematical definition but moreover the physical interpretation (Lines 359-363).

Response: Thanks for your suggestion. GW drag is the momentum released after the GW wave is broken, which is a parameter directly output in WACCM. GW has no direct parameters in SD-WACCM. GW drag does affect DW1 amplitude and phase, but in SD-WACCM, phase anomaly has not changed much (less than 2 hours in figure R8) in El Niño years. We added the Figures S3 and S4 as Figures 3 and Figure 4 in the revised manuscript, as well as more detailed description of the GW forcing (lines 396-407).

The zonal wind DW1 tide can be written as $U' = A*\cos(\omega*(t-\varphi)-s\lambda)$, where A and φ are the amplitude and phase of DW1 tide, ω ($\omega = 2\pi/24$) is DW1 frequency, λ is longitude and s ($s = 2\pi/360$) is zonal wave number of DW1. The time tendency of zonal wind can be written as: $\frac{\partial U'}{\partial t} = \omega*A*\cos(\omega*(t-\varphi)+\frac{\pi}{2}-s\lambda) = \omega*A*\cos(\omega*(t-(\varphi-6))-s\lambda)$;

The phase of the DW1 tide time tendency leads the tide itself by 6 hours. To evaluate the effect of GW forcing on the DW1 tide during December-January-February (DJF), the GW forcing can be calculated as: $GW_{forcing} = GW_{drag}*\cos(\omega*(\varphi_{GW}-(\varphi_U-6)))$;

Where GW_{drag} is GW drag, and φ_{GW} and φ_U are the phase of DW1-GW and DW1-U.

To evaluate the impact of GW on DW1, both the amplitude and phase of GW drag should be considered. When the phase of the GW drag is consistent with the tidal wind time tendency (in phase), the GW will increase the tide, vice versa. The effect of gravity wave changes on tides, which is defined as GW forcing in this study, could be estimated by projecting the GW drag on the time tendency of DW1-U.

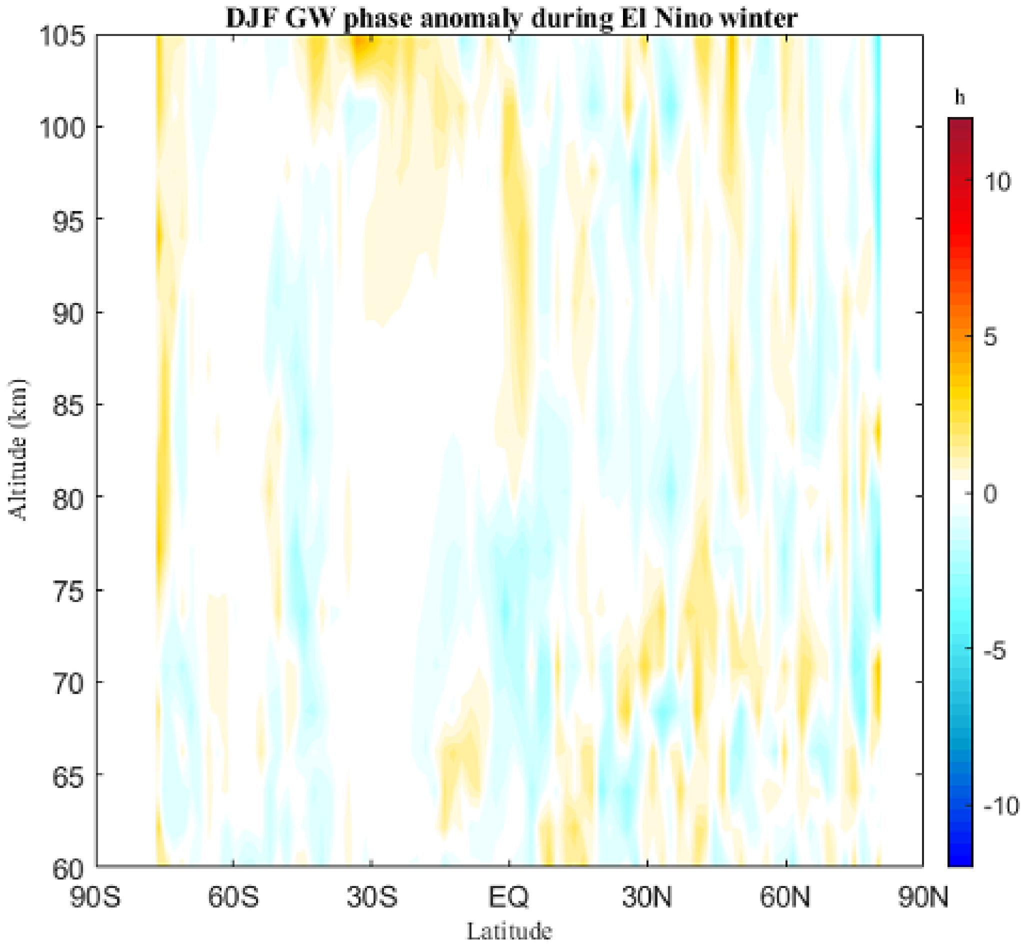

Figure R8. The zonal mean GW drag phase anomaly during El Niño winter due to convective in SD-WACCM.

Summary

10. I find it quite unusual not to have a Discussion section in a manuscript. The authors may consider to add this section, particularly to provide a “big picture” perspective for readers and remind them the importance of your study.

Response: Thanks for your suggestion. We added a discussion in lines 443-485 in the revised manuscript. By using SABER observation, the MLT DW1 amplitude in winter is negative response to ENSO in our study. Compare with SD-WACCM simulation and SABER observation, we propose three possible mechanisms. The first main mechanism is the excitation of HR, as the source of tidal generation in the stratosphere. During the process of tidal uploading from the stratosphere to the MLT region, the ratio of the absolute and planetary vorticity R played a role in the variation of DW1. In the MLT region, the effect of GW forcing on DW1 plays a large role in the simulation of SD-WACCM. This may be caused by convection being affected by ENSO, but due to the lack of observations, we cannot verify this conclusion. The response of DW1 to ENSO is not significant in 95 km, and we propose several possible mechanisms to explain this problem. According to previous research (Forbes et al. 1989), the enhancement of the zonal wind (observed by meteor radar at KT) will lead to an increase in the vertical wavelength at 95 km and a decrease in the Rayleigh friction coefficient, resulting in a tidal enhancement in El Niño winter. Using SABER observations, the vertical wavelength of DW1 at 95km also decreased during El Niño winter, which is consistent with meteor radar. Another possible explanation is that the momentum generated by the dissipation of DW1 at 95km resulted in the change of the zonal mean zonal wind. In El Niño winter, DW1 decreases at 90-100km, resulting in less DW1 dissipation at 95km (a bit like the voltage stabilizer at 95km, when the tide increases, it will dissipate more, and vice versa). Also, it may be the difference in the damping and forcing of tides caused by changes in gravity waves caused by ENSO at different heights. However, there is no corresponding observational gravitational wave data, so there is no way to analyze it. To solve this problem, we need more data and simulations for further research.

Response to the comments are also presented in the pdf file as supplementary.

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Please also note the supplement to this comment:
https://acp.copernicus.org/preprints/acp-2021-884/acp-2021-884-AC3-supplement.pdf