Response to reviewers

Reviewer #1 (Comments to Author (shown to authors):

In general it’s a thoughtful analysis of an important issue, the effect of El Niño on tidal oscillations in the mesosphere and lower thermosphere (MLT). It may be that this paper is more relevant to Annales Geophysique since, while it contains some detailed analysis of tropospheric effects, its ultimate intent is to understand the MLT. However, there is a larger issue- that of novelty. A recent paper by Vitharana et al., (JGR, 2021, doi:10.1029/2021JA029588) quite clearly states and demonstrates the anti-correlation between DW1 and El Niño.

And they both attribute similar causes. Thus compare: Vitharana ”due to changes in tropospheric forcing” vs. Cen “heating rates in the tropical troposphere”. And both analyze SABER data.

Certainly there are areas where Cen’s analysis can be deeper than Vitharana so Vitharana should not be considered the last word. For example, while the negative correlation is now established, there are the relative roles of different components of the effect (heating, filtering by stratospheric winds, GW forcing) that the present work can contribute. Furthermore, Vitharana appears to misquote Pedatella and Liu, 2012 by saying that their results are consistent with that older reference. When in fact, I concur with the present authors in saying that Pedatella and Liu reached the opposite conclusion. But this present submission should be reworded and re-oriented to be following Vitharana’s analysis. This probably means more work on “fleshing out” the details of the causes, for example the GW effect (which seems pretty clear in Figure 6). Their conclusions presently seem more like a simple listing- but I think they could, and should, give more information on the relative importance- perhaps one cause is more important at one altitude for example? (relevant to 4th and 5th bullets below)

1. I do not see where Ramesh showed a positive correlation between MLT DW1 and El Niño as stated on lines 94-95. Ramesh had lots of "predictors" and it wasn't clear what was forcing what. Perhaps the authors could clarify if I've missed something.

Response: Thanks for your suggestion. As added in lines 101-105 in the revised manuscript, "As suggested by the WACCM version 6 simulations with self-generated QBO and ENSO, Ramesh et al. (2020) illustrates the linear response of latitude-pressure variation of DW1-T to the seven predictors including ENSO in four seasons. They suggest that the response of DW1 to ENSO is significantly positive in the equatorial MLT region during the NH winter (Figure 5 in Ramesh et al. 2020)."

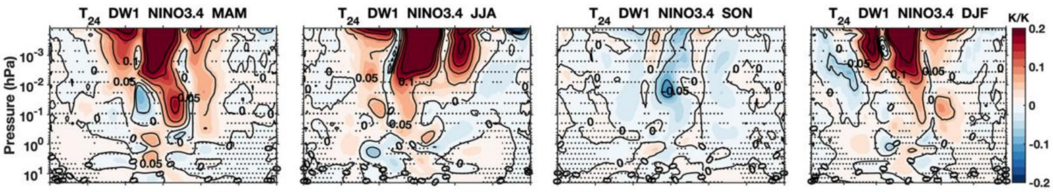

Figure R1 (Figure 5 in Ramesh et al., 2020): The seasonal variation of latitude-pressure distribution of ΔT24 responses to Niño3 averaged for three WACCM6 realizations. The responses in stippled regions are not significant at the 95% confidence level ($p > 0.05$). Contour intervals = 0.05 K/K, (The fourth row of figure 5 in Remash et al., 2020).

2. There is not a clear statement as to what SABER shows for the overall structure of the tide compared to WACCM. Do the authors agree with Vitharana? In which case, they can just state that, but also refer to the relevant figure in Vitharana. This is relevant to the 4th bullet below.

Response: To compare the distribution of the climatological mean DW1 tidal amplitude of SD-WACCM simulation with SABER observation, Figure R2 (Figure 1 in the revised manuscript) shows the average DW1 temperature amplitude in SABER observation and SD-WACCM during the winter from 2002 to 2013. The boreal winter (December-January-February, DJF) mean amplitude of DW1 temperature is the largest (~12 K) in the equatorial mesopause region extracted from TIMED/SABER observation. Although the mean amplitude in SD-WACCM is weaker than that in SABER, the distribution of the DW1 T amplitude in SD-WACCM simulation is quite similar to that derived from SABER observation, with the maximum at 90-100 km above the equator. There are some differences between SABER and SD-WACCM: SABER has a weaker peak above the equator at 70-80 km, but this peak cannot be seen in SD-WACCM. The interannual variation of the equatorial MLT DW1-T amplitudes weighted by phase difference in SABER and SD-WACCM also agree well during the northern winter of 2002-2014 (Figure 2a and 2b in the revised manuscript).

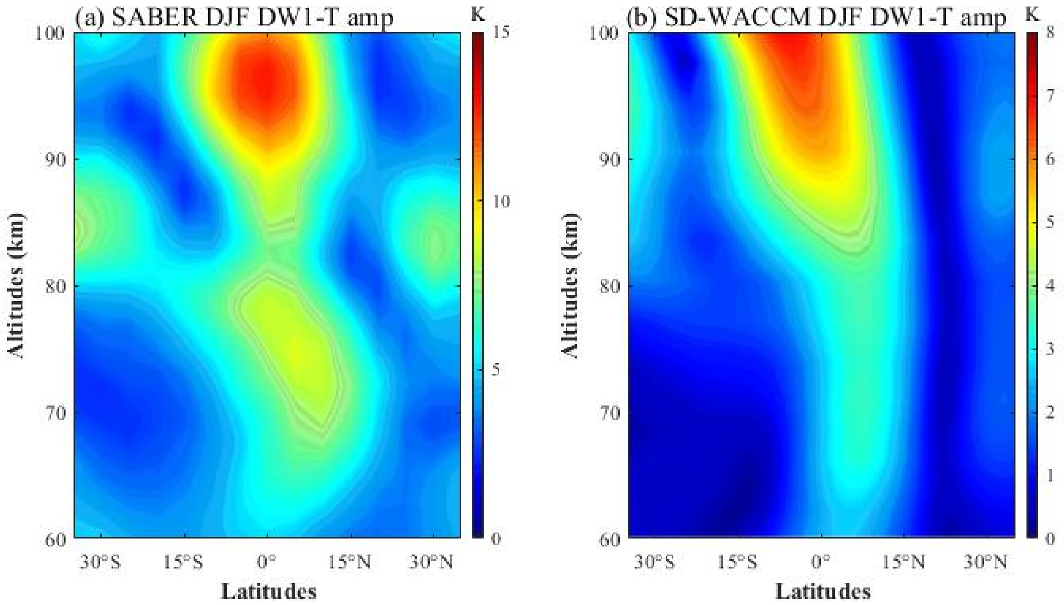

Figure R2 (Figure 1 in the revised manuscript). (a) The average DW1 temperature amplitude of SABER observation during 2002-2013 winter (DJF, Dec-Jan-Feb). (b) the same as (a), but for SD-WACCM.

As mentioned above, Vitharana et al. (2021) have stated that the MLT DW1 negatively responds to ENSO by calculating the multi-linear regression for all the months from 2003-2016. However, it is noted that the responses of MLT DW1 tide vary quite a bit to ENSO among different seasons (e.g. Zhou et al., 2018; Kogure et al., 2021). Thus, calculating the regression by binning the data among different months together may underestimate the actual response of MLT DW1 tide during the particular season due to the masking between different responses with each other. Indeed, the negative responses of MLT DW1 to ENSO during the winter are approximately five times larger than those estimated from all the months' data (Vitharana et al., 2021), while the location of the most significant responses is also different. It should be pointed out that the MEI indices were "normalized" by setting the maximum value to 1 in Vitharana (2021), which is different from the method we used (set the standard deviation to 1). If we also adopt the same method as Vitharana et al. (2021) did, the regression coefficients of MLT DW1 amplitude response to ENSO in winter (Figure R3) is over -3 K per index at 90 and 100 km, while the maximum of regression coefficients in Vitharana (2021) is only -0.6 K per index at the same region. The comparison between our results with those of Vitharana et al. (2021) has been rewritten in lines 82-93 and 248-253 in the revised manuscript.

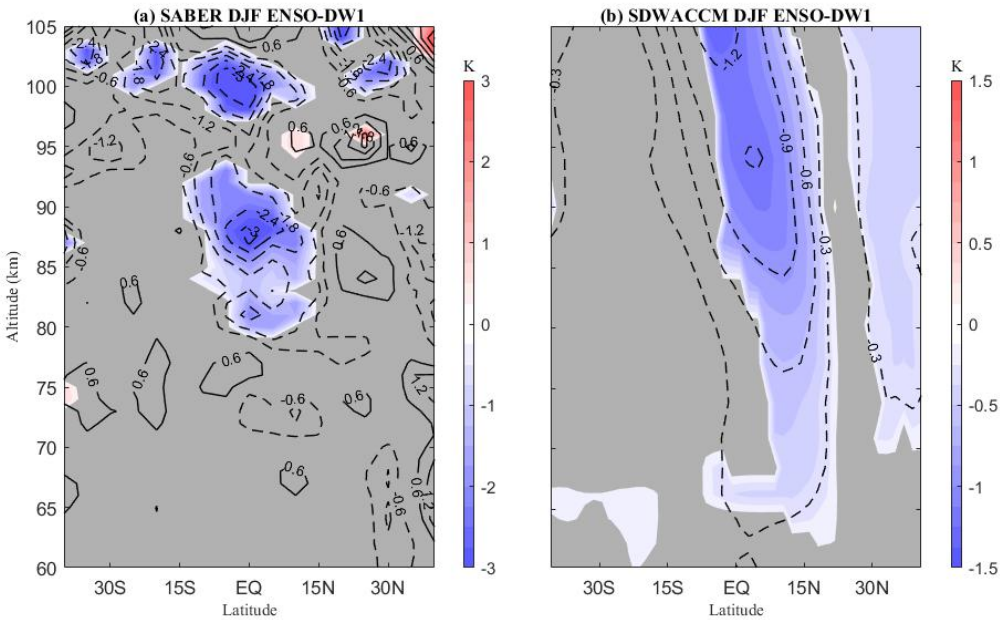

Figure R3. The linear regression coefficient of normalized Niño3.4 in SABER (a) and SD-WACCM (b) DW1-T. The contour interval is 0.6 K for SABER and 0.3 K (N3.4) for SD-WACCM. Red represents positive response and blue represents negative; the gray regions denote confidence levels below 95% for F-test.

3. I notice the authors use WACCM4, not WACCM6 which is the latest. While this is probably acceptable, they should at least note this and offer any comments on possible differences. For example, WACCM6 uses a self-consistent QBO (which might allow for better characterization of feedbacks?) and a different (better?) GW scheme as well as higher spatial resolution.

a. I'm not sure I fully understand line 249, but it does seem to speak to the question of feedbacks between QBO and ENSO which, if so, is relevant to the question of the WACCM model version number. Can they clarify?

Response: Thanks for your suggestion. WACCM is a high-top model that can be used as the atmospheric component of the Community Earth System Model (CESM1) of the National Center for Atmospheric Research. WACCM4 is based on the Community Atmosphere Model, version 4 with the vertical model domain extended to ~145 km.

The "Specified dynamics" version of WACCM4 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). With the relaxation, the atmospheric variables such as QBO are consistent with the reanalysis in the troposphere and stratosphere.

WACCM6 is the latest version of WACCM in CESM2, transitions to higher horizontal and vertical resolution, which can simulate finer structures in the atmosphere. WACCM4 includes a representation of the quasi-biennial oscillation (QBO), achieved by relaxing equatorial zonal winds between 86 and 4 hPa to observed interannual variability (Marsh et al. 2013). Compared with WACCM4, the QBO in WACCM6 is self-generated (Gettelman et al. 2019). WACCM6 is able to simulate, albeit imperfectly, the QBO, the equatorial zonal wind propagation, which in observations has an average period of ~28 months. Similar to WACCM5 (Mills et al., 2017), WACCM6 simulates a reasonable QBO with 70 levels in a free running configuration.

Both WACCM4 and WACCM6 can be run fully coupled to active ocean and sea ice model components or use specified SST (Marsh et al., 2013). Pedatella & Liu (2012 and 2013) utilize the WACCM4 with self-generated ENSO and no QBO signal, while Ramesh et al. (2020) use the WACCM6 simulations with self-generated ENSO and QBO. Different from these two simulations, the SST which follows the observation is prescribed in SD-WACCM. And the SD-WACCM atmospheric variables such as QBO are consistent with the reanalysis in the troposphere and stratosphere.

As suggested by Figure 5 in Ramesh et al. (2021), the equatorial MLT DW1 positively responds to ENSO in the northern hemispheric winter, which is the opposite of that in the SABER observations and SD-WACCM simulations. The difference in generating ENSO and QBO among different versions of the model could play a role in the divergence in the ENSO-DW1 relationship.

Two main adjustable parameters in the frontal gravity wave source specification have been changed since WACCM4 due to the increased horizontal resolution in WACCM6: The frontogenesis threshold in WACCM6 is set to 0.108 K^2 (100 km)$^{-2}$ $\cdot h^{-1}$ and the source stress of frontally generated waves is set to $\tau_b=3\times10^{-3}$ Pa (Gettelman et al. 2019). In WACCM4, the frontogenesis threshold is set to 0.045 K^2 (100 km)$^{-2}$ $\cdot h^{-1}$ and the source stress of frontally generated waves is set to $\tau_b=1.5\times10^{-3}$ Pa. Different parameterization schemes and resolutions may have some effects on DW1-ENSO relationship. However, the completely opposite DW1-ENSO relationship in SD-WACCM and WACCM6 should not be simply attributed to the gravity waves. Indeed, DW1-ENSO relationship in WACCM4 are similar to those in WACCM6 (Pedatella & Liu, 2012 & Ramesh et al., 2021). Other factors which differ in different version of WACCM could affect the DW1-ENSO connection, more investigation and comparison between models are needed to determine the effect of the gravity wave parameterization is in the future work.

4. The effect of R on DW1 seems to maximize at latitudes below the peak of the DW1 *(reference is to Figure 5 but this is where a statement or a figure as to the overall structure of DW1 would be helpful). As a result, I wonder whether it is really relevant. Or at least not at the peak- this is where going beyond a simple listing of causes could be useful.*

Response: Thanks for the suggestion. The ratio of the absolute and planetary vorticity R is equivalent to changing the planet rotation rate. In classical theory, the vertically propagating DW1 is restricted near the equator due to the planet's rapid rotation. Therefore, a faster rotation rate (positive R anomalies) will suppress the latitudinal band (i.e., waveguide) where DW1 can propagate vertically. On the other hand, the slower rotation rate (negative R anomalies) favors the vertical propagation and is thus able to enhance the amplitude of DW1 at the low latitudes (Mclandress. 2002b). When the ratio of the absolute and planetary vorticity R-value at a certain height becomes larger, the upward propagation of tide is suppressed, which lead to weaker tides above there. We modified Figure R4 (Figure 6 in the revised manuscript) to show significant areas of the multivariate linear regression (MLR) coefficient of R on Niño 3.4. The green thick solid line represents the sum of the equatorial ratio of the absolute and planetary vorticity R values (15-30°N and 15-30°S), and the thick lines indicate the area where the regressed coefficients are significant. 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.

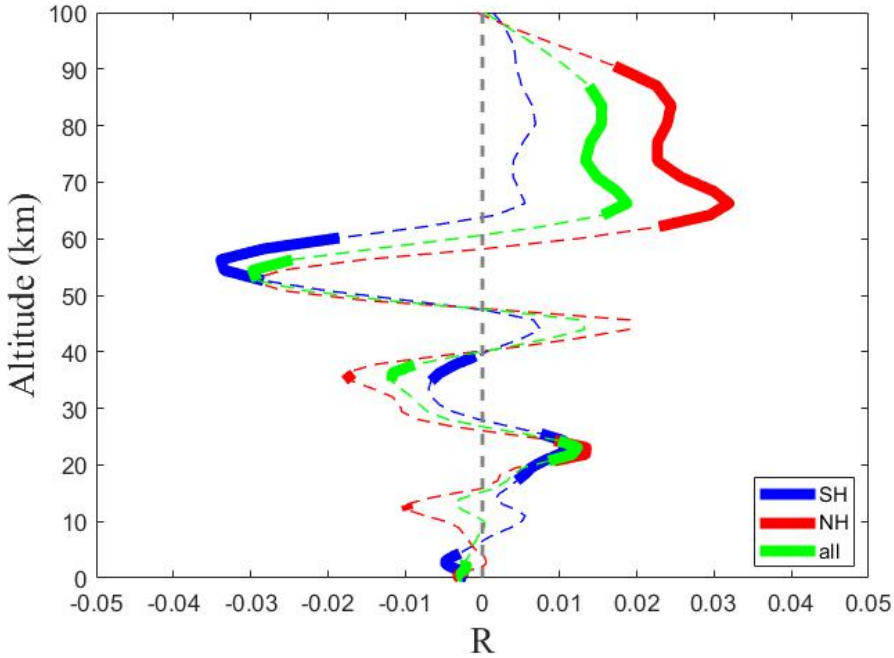

Figure R4 (Figure 6 in the revised manuscript). The anomaly of the ratio of the absolute and planetary vorticity, δR. The thin, dashed red, blue and green lines denote the averages of the Northern Hemisphere (from 15°N to 30°N), Southern Hemisphere (from 15°S to 30°S) and the whole (15-30°N and 15-30°S) , respectively. The thick, solid lines denote confidence levels below 95% for the F test.

5. In general, I think the GW analysis could use more detail. Overall, I think it's believable, but I would like more information- specifically I think they should put more effort on teasing out the effects of source forcing and filtering that they allude to in lines 377 and 378. If the gravity waves in WACCM are linked to convection, then shouldn't they be able to quantify the change in GW forcing more rigorously? Presumably there are certain phase speeds which are more or less relevant here?

Response: Thanks for your suggestion. In this study, the GW analysis with respect to the response of diurnal tide to ENSO is based on the parameterized GWs drag from the "specified dynamics" WACCM. In the standard setup of SD-WACCM4, the gravity wave source spectrum includes wave components with phase velocities in the range from -80 to +80 m s^{-1}, at intervals of 2.5 m s^{-1} (Beres et al. 2005). In SD-WACCM, the GW drags are separated with respect to different excitation sources, while the detailed information such as the phase speed are not available in the model output.

The discussion between GW drag generated by frontal systems and convection has been added in lines 387-388 in the revised manuscript as “The GW in the tropics is primarily induced by the convection, while the GW in the middle to high latitudes is mainly generated by the frontal systems (Figure S5, S6).”.

Reference

Beres, J., Garcia, R. R., Boville, B. A., & Sassi, F. (2005). Implementation of a gravity wave source spectrum parameterization dependent on the properties of convection in the Whole Atmosphere Community Climate Model (WACCM). Journal Of Geophysical Research-Atmospheres, 110, D10108. http://doi.org/10.1029/2004JD005504

Gettelman, A., Mills, M. J., Kinnison, D. E., Garcia, R. R., Smith, A. K., Marsh, D., … Randel, W. (2019). The Whole Atmosphere Community Climate Model Version 6 (WACCM6). Journal Of Geophysical Research: Atmospheres, 124, 12380-12403. https://doi.org/10.1029/2019JD030943

Kogure, M., & Liu, H. (2021). DW1 tidal enhancements in the equatorial MLT during 2015 El Niño: The relative role of tidal heating and propagation. *Journal of Geophysical Research: Space Physics*, 126, e2021JA029342. https://doi.org/10.1029/2021JA029342

Kunz, A., Pan, L. L., Konopka, P., Kinnison, D., & Tilmes, S. (2011). Chemical and dynamical discontinuity at the extratropical tropopause based on START08 and WACCM analyses. Journal Of Geophysical Research, 116, D24302. https://doi.org/10.1029/2011JD016686

Marsh, D., Mills, M., Kinnison, D. E., & Lamarque, J. -F. (2013). Climate change from 1850 to 2005 simulated in CESM1(WACCM). Journal Of Climate, 26, 7372-7391. https://doi.org/10.1175/JCLI-D-12-00558.1

Mills, M. J., Richter, J. H., Tilmes, S., Kravitz, B., MacMartin, D. G., Glanville, A. S., … Kinnison, D. E. (2017). Radiative and chemical response to interactive stratospheric sulfate aerosols in fully coupled CESM1(WACCM). Journal Of Geophysical Research: Atmospheres, 122, 13061-13078. https://doi.org/10.1002/2017JD027006

Ramesh, K., Smith, A. K., Garcia, R. R., Marsh, D. R., Sridharan, S., & Kishore Kumar, K. (2020). Long-term variability and tendencies in migrating diurnal tide from WACCM6 simulations during 1850–2014. *Journal of Geophysical Research: Atmospheres*, 125, e2020JD033644. https://doi.org/10.1029/2020JD033644

Vitharana, A., Du, J., Zhu, X., Oberheide, J., & Ward, W. E. (2021). Numerical prediction of the migrating diurnal tide total variability in the mesosphere and lower thermosphere. Journal of Geophysical Research: Space Physics, 126, e2021JA029588. https://doi.org/10.1029/2021JA029588

Zhou, X., Wan, W., Yu, Y., Ning, B., Hu, L., and Yue, X. (2018). New approach to estimate tidal climatology from ground-and space-based observations. *Journal of Geophysical Research: Space Physics, 123, 5087– 5101*. http://doi.org/10.1029/2017JA024967

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.

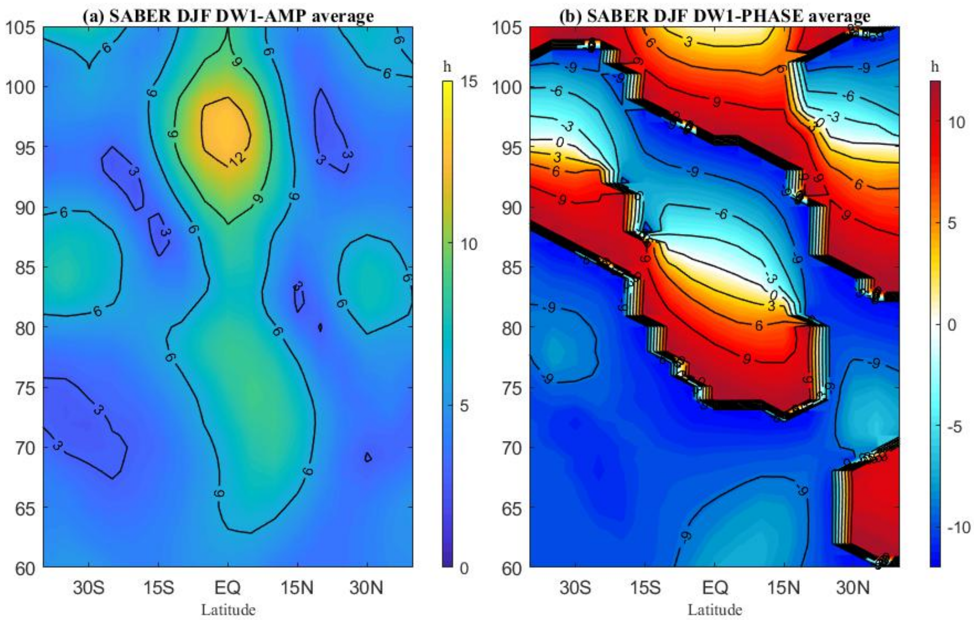

Figure R1 (Figure S1 in the revised supplement). (a) The average DW1 temperature amplitude of SABER observation during 2002-2020 winter (DJF, Dec-Jan-Feb). (b) the same as (a), but for phase.

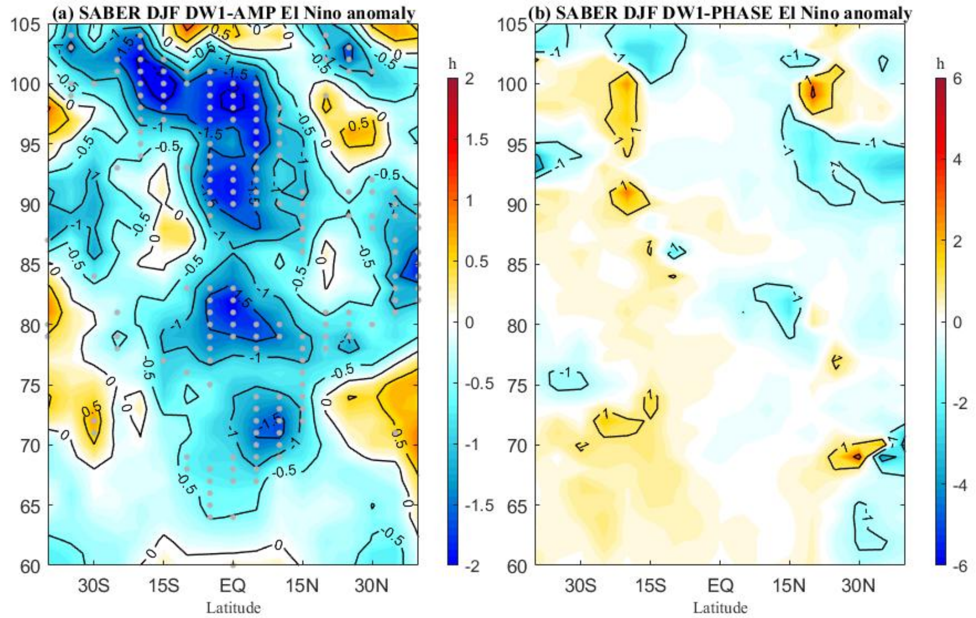

Figure R2 (Figure S2 in the revised supplement). Dec-Jan-Feb mean of the SABER DW1-T (a) amplitude and (b) phase anomaly during El Niño years. Stippling indicates statistical significance at the 95% level using Student's T test.

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

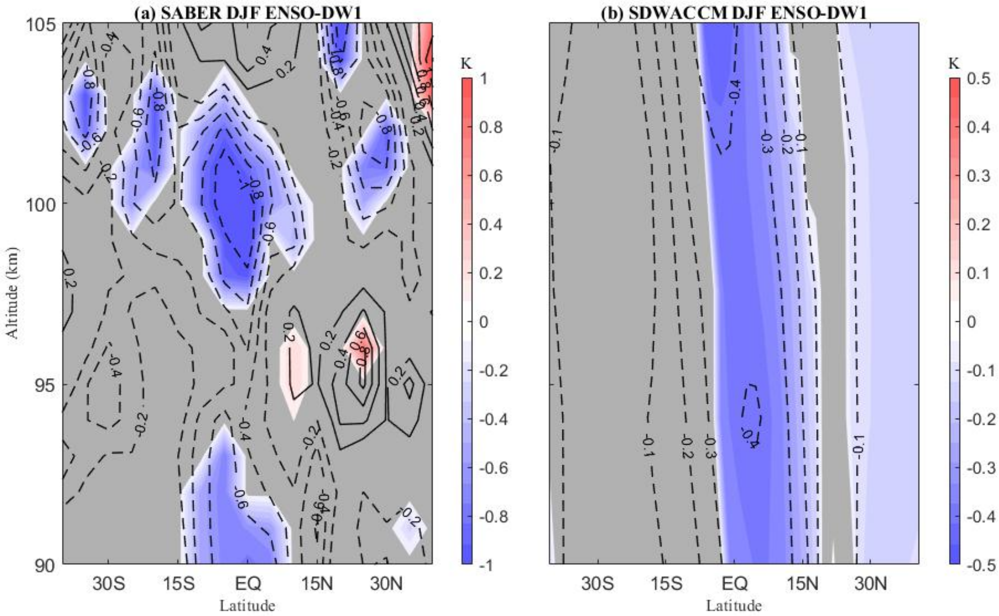

Figure R3 (Figure 2 in the original manuscript). The linear regression coefficient of normalized Niño3.4 in SABER (a) and SD-WACCM (b) winter DW1-T. The contour interval is 0.2 K for SABER and 0.1 K for SD-WACCM. Red represents a positive response, and blue represents a negative response; the grey regions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

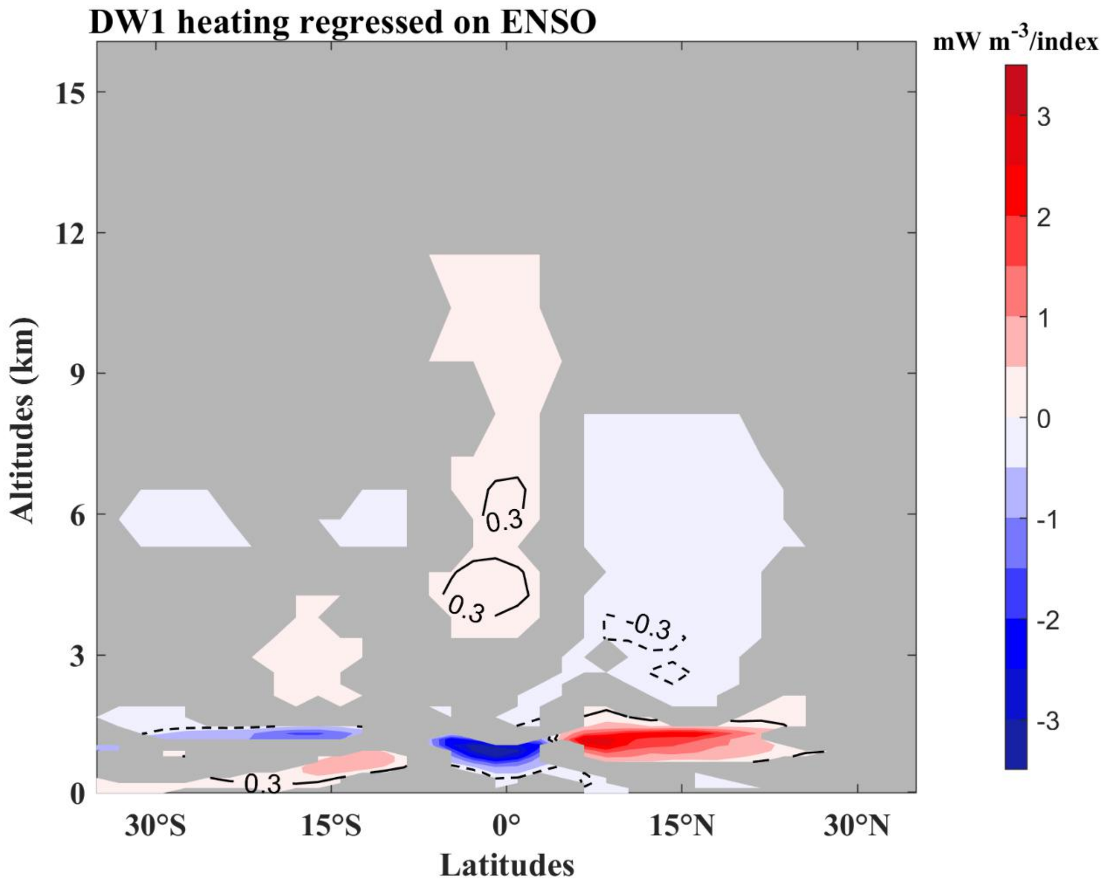

Figure R4 (Figure 5 in the revised manuscript). The linear regression coefficient of normalized Niño3.4 in SD-WACCM heating amplitude (mW/m^3 per index) during 1979-2013 winters (DJF). Red represents a positive response, and blue represents a negative response; the grey regions denote confidence levels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

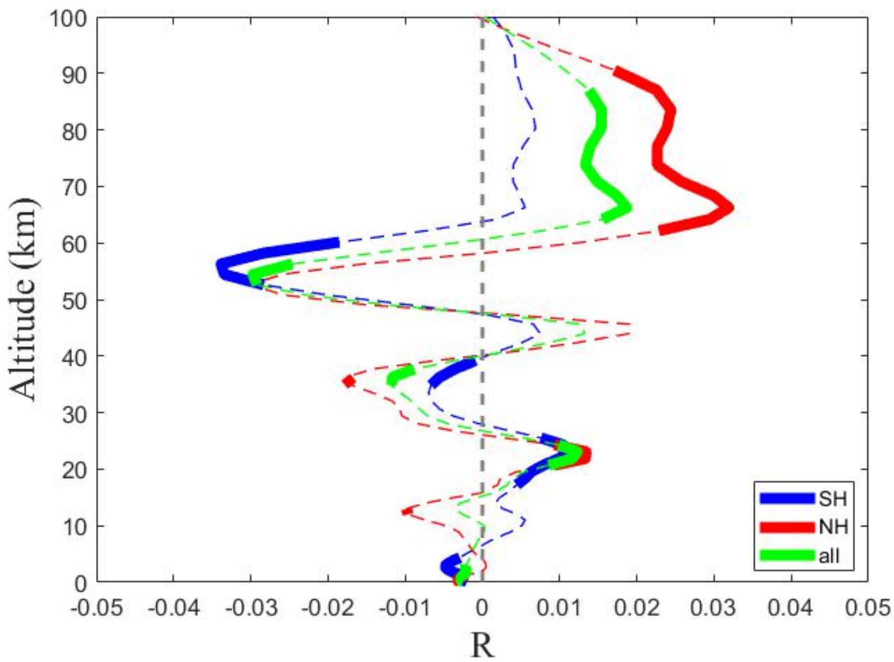

Figure R5 (Figure 6 in the revised manuscript). The anomaly of the ratio of the absolute and planetary vorticity, δR. The thin, dashed red, blue and green lines denote the averages of the Northern Hemisphere (from 15°N to 30°N), Southern Hemisphere (from 15°S to 30°S) and the whole (15-30°N and 15-30°S) , 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.

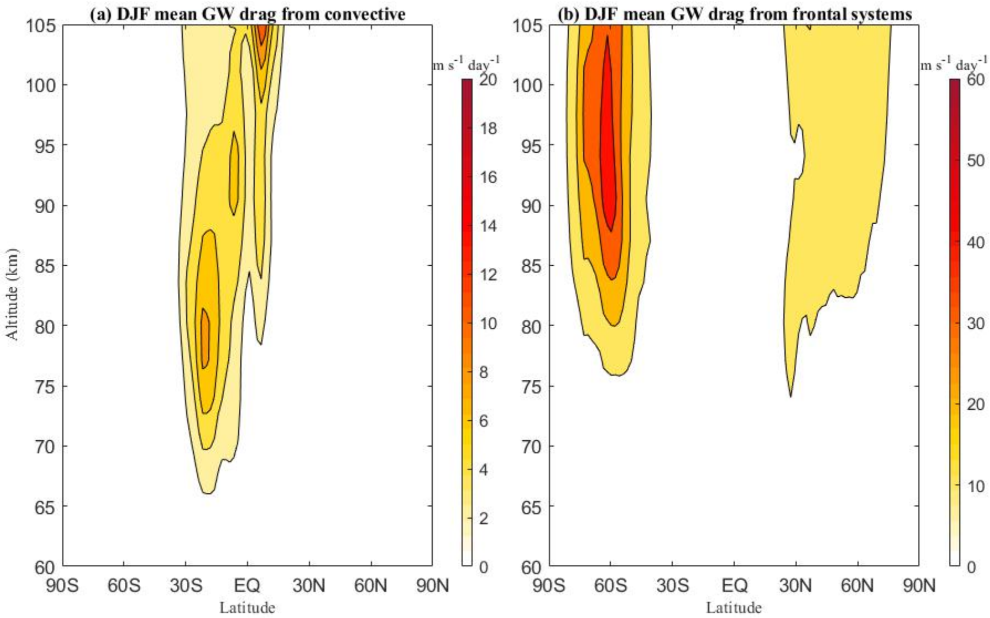

Figure R6 (Figure S5 in the revised supplement). The zonal mean GW drag average in winter due to convective (a) and the frontal systems (b) in SD-WACCM.

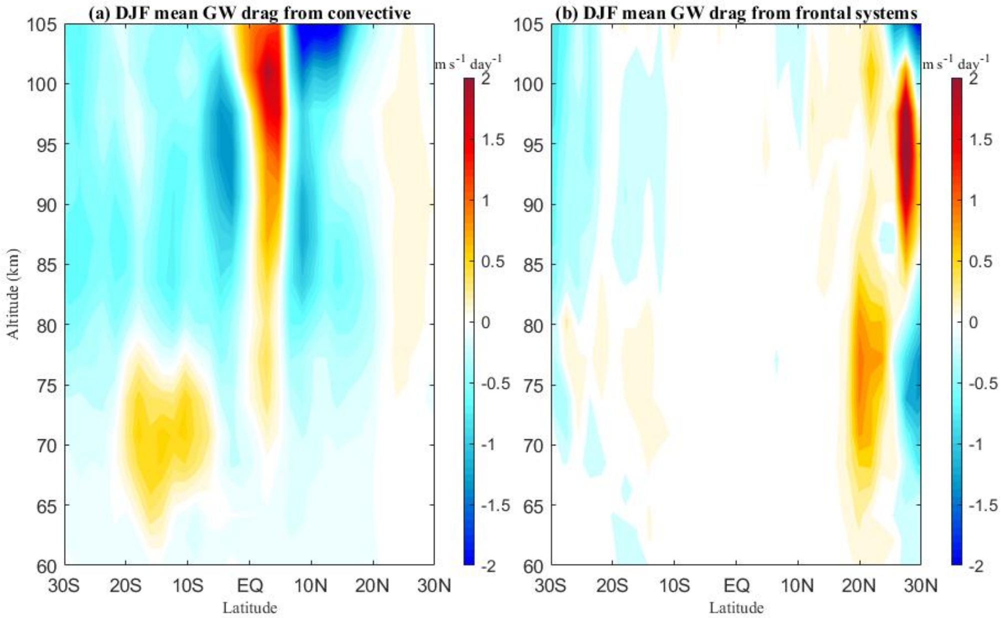

Figure R7 (Figure S6 in the revised supplement). The zonal mean GW drag anomaly during El Niño winter due to convective (a) and the frontal systems (b) in SD-WACCM.

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:

$$GW_{\mathrm{forcing}} = GW_{drag} * \cos(\omega * (\varphi_{GW} - (\varphi_{U} - 6)));$$

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.

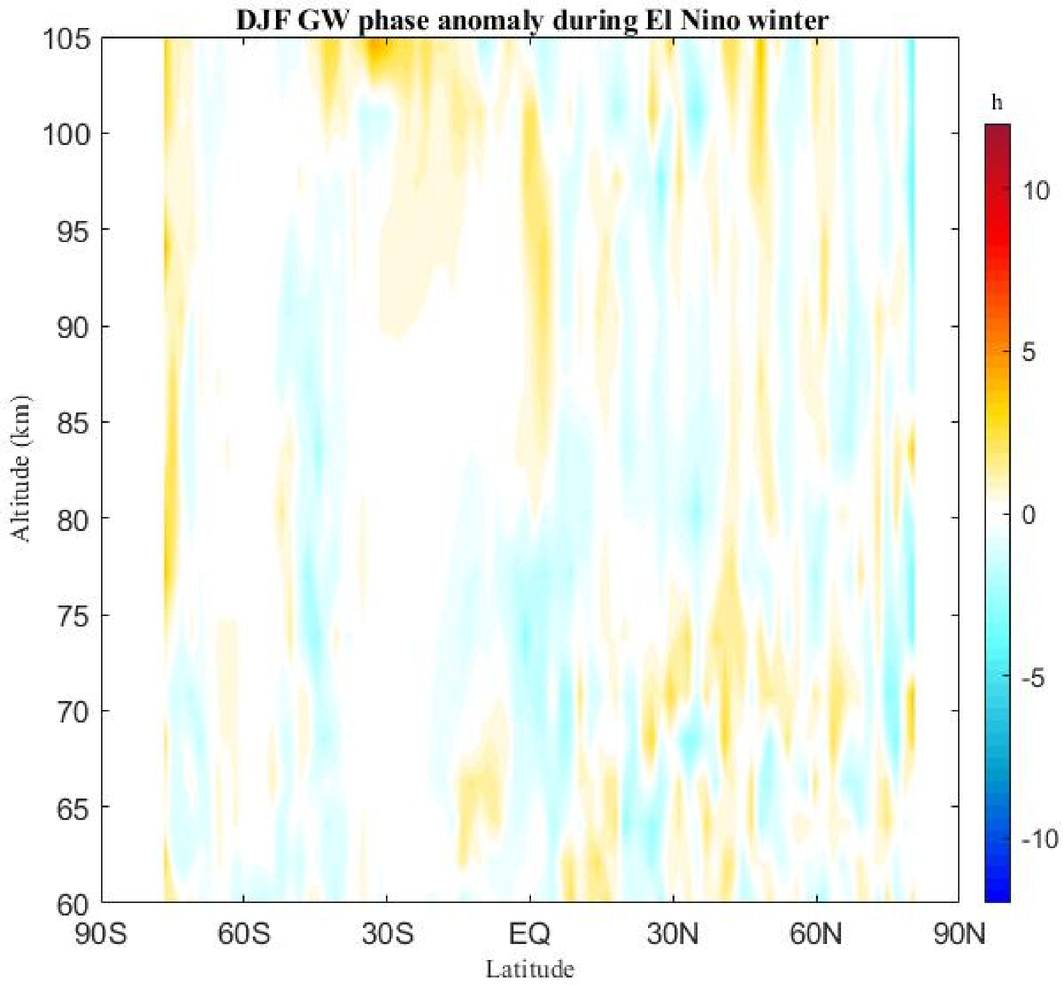

Figure R8. The zonal mean GW drag phase anomaly during El Niño winter due to convective in SD-WACCM.

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.

Reference

Forbes, J. M. , & Vincent, R. A. (1989). Effects of mean winds and dissipation on the diurnal propagating tide: an analytic approach. *Planetary & Space Science, 37(2), 197-209.* https://doi.org/10.1016/0032-0633(89)90007-X

Fritts, D. C. (1989), A review of gravity wave saturation processes, effects, and variability in the middle atmosphere, *Pure Appl. Geophys., 130, 343–371.* http://doi.org/10.1007/BF00874464

Fritts, D. C., Alexander, MJ (2003). Gravity wave dynamics and effects in the middle atmosphere, *REVIEWS OF GEOPHYSICS*, 41: 1 (1003) http://doi.org/10.1029/2001RG000106)

Kunz, A., Pan, L. L., Konopka, P., Kinnison, D., & Tilmes, S. (2011). Chemical and dynamical discontinuity at the extratropical tropopause based on START08 and WACCM analyses. *Journal Of Geophysical Research, 116, D24302.* https://doi.org/10.1029/2011JD016686

Liu, H.-L., Bardeen, C. G., Foster, B. T., Lauritzen, P., Liu, J., Lu, G., ...Wang, W.(2018). Development and validation of the Whole Atmosphere Community Climate Model with thermosphere and ionosphere extension (WACCM-X 2.0). *Journal of Advances in Modeling Earth Systems*, 10, 381–402. https://doi.org/10.1002/2017MS001232

Liu, X., et al. (2021). Global balanced wind derived from SABER temperature and pressure observations and its validations. Earth Syst. Sci. Data, 13, 5643–5661. https://doi.org/10.5194/essd-13-5643-2021

Ramesh, K., Smith, A. K., Garcia, R. R., Marsh, D. R., Sridharan, S., & Kishore Kumar, K. (2020). Long-term variability and tendencies in migrating diurnal tide from WACCM6 simulations during 1850–2014. *Journal of Geophysical Research: Atmospheres*, 125, e2020JD033644. https://doi.org/10.1029/2020JD033644

Reviewer #3 (Comments to Author (shown to authors):

1. *I agree with the first reviewer that this paper should compare with Vitharana et al. (2021), where the negative correlation between DW1 and ENSO is clearly established, Vitharana also used SABER data.*

Response: The comparison between our results with those of Vitharana et al. (2021) has been rewritten in lines 82-93 and 248-253 in the revised manuscript.

2. The significance of this paper lies in the physical mechanisms. I am surprised to see all three sources (tropospheric heating, wind filtering and gravity waves) are pulling in the same direction, making DW1 amplitude smaller in the El Niño phase. For tropospheric heating, the Hough mode analysis is well done. The tropospheric heating however presents positive and negative correlations with DW1 amplitude at different heights and latitudes. The authors averaged the heating between 0-16 km and 35 N and 35 S and found there is an overall decreasing heating rate during El Niño. How do you justify the choice of the altitude and latitude range? Apparently, if you calculate the correlation with a different range, you can get a totally different conclusion.

Response: Thanks for your comment. According to the tidal theory, Not only HR near the equator that affects DW1 hough (1, 1) but the heating in global troposphere. For example, the major heating for H_2O in equinox is associated with the symmetric (1, -2) mode, and the (1, 1) and (1, -4) symmetric modes are excited with about equal strength with amplitudes ~20-25% of the (1, -2) heating rates (Volland and Hans, 1988; Forbes 1982). Therefore, it is more reasonable to calculate the mass weighted heating rate covering all the area of tropical troposphere (35°S-35°N, 0-16 km) to investigate the effect of tropospheric heating on tides. The correlation coefficient between 15 km DW1-T and the mass weighted HR of the whole tropical troposphere (35°S-35°N, 0-16 km) is 0.45 (significance at the 95% level according to the Student's T test). The correlation between DW1-T and the HR over the whole tropical troposphere is higher than those between DW1-T and the HR over the regions suggested by previous studies (Table 2). Although the correlations with MLT DW1 tide are weaker or even insignificant, the HR averaged over different region as selected by previous studies also suggests negative response during the El Niño winters.

The comparison between HR calculated in different areas has been discussed in lines 328-343 in the revised manuscript.

Table 2 in the revised manuscript: The correlation coefficient between the DW1 T amplitude at 15 km and the mass-weighted HR in different areas during the winters of 1979-2014. The bold numbers indicate that the correlation coefficients are significant at the 95% level. The MLR coefficient on the normalized Niño3.4 index (10^{-3} mw m^{-3} $index^{-1}$) is also exhibited.

Altitude and latitude ranges	0-16 km, 35°N-35°S)	0-12 km, 35°N-35°S)	5-10 km, 35°N-35°S)	5-10 km,20° N-20°S)
Correlation coefficient	**0.45**	**0.36**	0.32	0.32
MLR coefficient on Niño3.4	-3	-10	-26	-9

3. Similar scenario happened to R, the range is chosen between 15 and 35 degrees in each hemisphere, how is this range chosen? does the conclusion change if a different range is chosen? R is positive and negative several times below the MLT, how does that affect DW1 propogation?

Response: Thanks for your suggestion. To investigate the effect of the wave guide on the upward propagation of tide near the equator, the R near the tropics (15-30°) are considered. However, Since f tends to 0 near the equator, the $R = (\overline{\zeta} + f)/f$ tends to infinity. The R over the similar range are also adopted to McLandress et al. (2002b) and Wu et al. (2017).

We modified Figure 6 to show the significance of the regressed R on Niño index. The green thick solid line represents the mean value of the ratio of the absolute and planetary vorticity (R) at the subtropics (15-30°N and 15-30°S), and the thick lines indicate the area where the regressed coefficients are significant at 95% level. The R response to ENSO is positive at 60-100 km in the northern subtropics and 65-100 km in the southern subtropics, which would suppress the upward propagation of the DW1 tide in the mesosphere and contribute to the negative response of the DW1 tidal wind.

Liu (2015) chose 10-40°N (S) to calculate the ratio of the absolute and planetary vorticity R. Figure R2 shows the R value between 10-40°N (S). It can be seen that only the mean R values at 60-80km are continuously significant, which is consistent with figure 6 (15-30°).

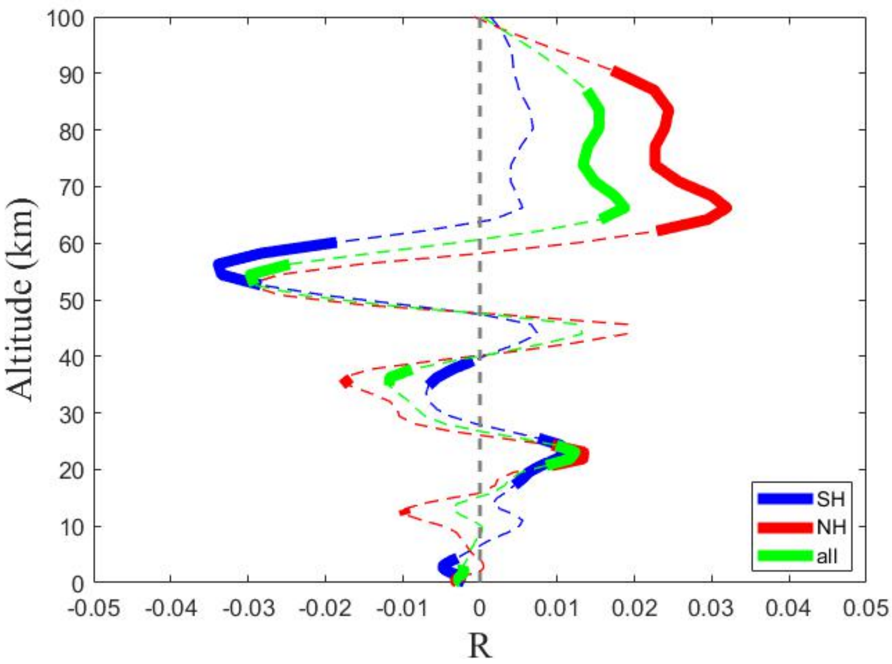

Figure R1 (Figure 6 in the revised manuscript). The anomaly of the ratio of the absolute and planetary vorticity, δR. The thin, dashed red, blue and green lines denote the averages of the Northern Hemisphere (from 15°N to 30°N), Southern Hemisphere (from 15°S to 30°S) and the whole (15-30°N and 15-30°S) , respectively. The thick, solid lines denote confidence levels below 95% for the F test.

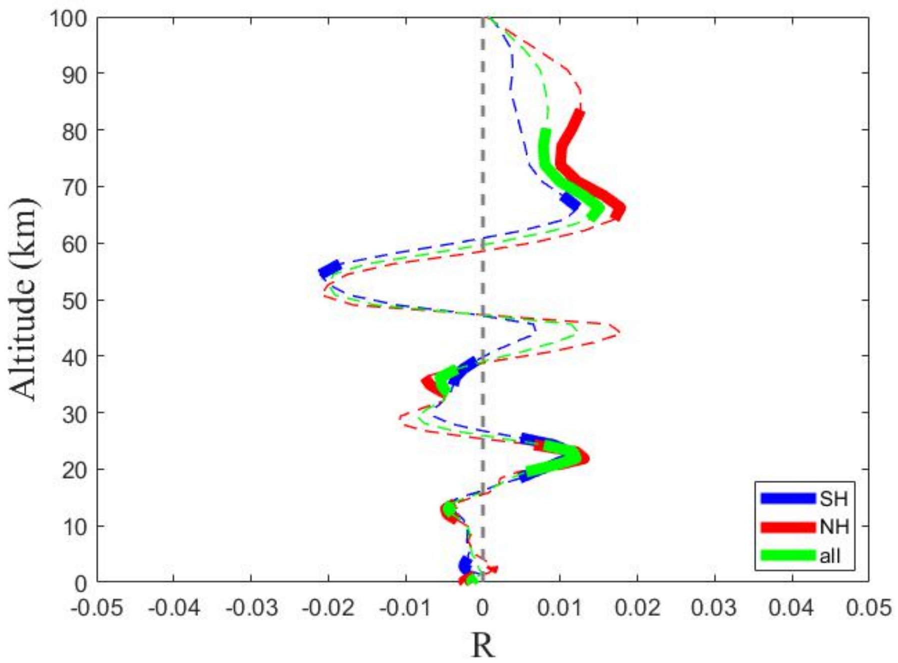

Figure R2. The linear regression coefficient of normalized Niño3.4 in δR (the anomaly of the ratio of the absolute and planetary vorticity). The thin, dashed red, blue and green lines denote the averages of the Northern Hemisphere (from 10°N to 40°N), Southern Hemisphere (from 10°S to 40°S) and the whole (10-40°N and 10-40°S), respectively. The thick, solid lines denote confidence levels below 95% for the F test.

4. I also agree with reviewer 1 that the third mechanism about gravity wave drag needs further investigation. I don't understand why the correlation between gravity wave drag and DW1 is negligible or even negative while the correlation between gravity wave forcing and DW1 is positive in the MLT region at all latitudes.

Response: Thanks for your suggestion. When gravity wave drag variability and tide tendency are close to orthogonal, the correlation between the two can be ignored, but after calculating the phase weight, the orthogonal changes of the two have been excluded, and only the gravity wave drag variability and the tide tendency in the same phase are calculated. So gravity wave forcing and tide may be significantly correlated, albeit at a time when gravity wave drag is less correlated with tide.

Similarly, if the GW drag in the same direction as the tidal tendency increases, which lead the tidal amplitude increases, then gravity wave forcing is positively correlated with the tide. But if the GW drag that is orthogonal to the tidal tendency decreases by a large margin in the same time, it is found that GW drag is negatively correlated with tide, although GW drag which is orthogonal to the tidal tendency does not actually change tide strength directly.

We have included more detailed analysis of GW drag in the main text, please see lines 379-407 in the revised manuscript.

Reference

Forbes, JM (1982). Atmospheric tides 1. Model Description and Results for the Solar Diurnal Component. *JOURNAL OF GEOPHYSICAL RESEARCH,* VOL. 87, NO. A7, PAGES 5222-5240, https://doi.org/10.1029/JA087iA07p05222

Kogure, M., & Liu, H. (2021). DW1 tidal enhancements in the equatorial MLT during 2015 El Niño: The relative role of tidal heating and propagation. *Journal of Geophysical Research: Space Physics*, 126, e2021JA029342. https://doi.org/10.1029/2021JA029342

Lieberman, R. S., Ortland, D. A., & Yarosh, E. S. (2003). Climatology and interannual variability of diurnal water vapor heating. Journal of Geophysical Research: Atmospheres 108(D3): https://doi.org/10.1029/2002jd002308

McLandress, C. (2002b), The seasonal variation of the propagating diurnal tide in the mesosphere and lower thermosphere. Part II: The role of tidal heating and zonal mean winds, J. Atmos. Sci., 59(5), 907–922, https://doi.org/10.1175/1520-0469(2002)059<0907:Tsvotp>2.0.Co;2.

Pedatella, N. M., & Liu, H. L. (2013). Influence of the El Niño Southern Oscillation on the middle and upper atmosphere. *Journal of Geophysical Research:* Atmospheres 118(5):2744–2755, https://doi.org/10.1002/Jgra.50286

Vitharana, A., Du, J., Zhu, X., Oberheide, J., & Ward, W. E. (2021). Numerical prediction of the migrating diurnal tide total variability in the mesosphere and lower thermosphere. Journal of Geophysical Research: Space Physics, 126, e2021JA029588. https://doi.org/10.1029/2021JA029588

Wu, Z., T. Li, and X. Dou (2017), What causes seasonal variation of migrating diurnal tide observed by the Mars Climate Sounder?, *J. Geophys. Res. Planets,* 122, http://doi.org/10.1002/2017JE005277.

Zhang, X., Forbes, J. M., & Hagan, M. E. (2010). Longitudinal variation of tides in the MLT region: 1. Tides driven by tropospheric net radiative heating. *Journal of Geophysical Research: Space Physics* , *115*, A06316, https://doi.org/10.1029/2009JA014897.

Zhou, X., Wan, W., Yu, Y., Ning, B., Hu, L., and Yue, X. (2018). New approach to estimate tidal climatology from ground-and space-based observations. *Journal of Geophysical Research: Space Physics, 123, 5087– 5101*. http://doi.org/10.1029/2017JA024967