We wish to thank the reviewer for their helpful comments. We have modified the manuscript as suggested. Below shows our responses to all the comments. Reviewer's comments are in bold red while our responses are in black. Note that, unless otherwise specified, all line numbers mentioned in the responses to comments refer to the numbers in the new (no tracking) manuscript.

REVIEWER 2:

Review of "Aura/MLS observes, and SD-WACCM-X simulates the seasonality, quasi-biennial oscillation and El Nino Southern Oscillation of the migrating diurnal tide driving upper mesospheric CO primarily through vertical advection", by Salinas et al.

Recommendation: Revisions.

This paper reports the morphology and long-term variations in the diurnal cycles of T and CO observed by MLS, and extracted from an SD run of WACCM-X. The objective is to determine whether CO can be interpreted as a passive tracer of tidal motion. The authors demonstrate that the structures of diurnal CO and T closely track each other in both the data and in WACCM-X. By computing the mass budget of CO in WACCM-X, they are able to attribute the presence of tidal CO to vertical advection. The diurnal CO is also found to vary at QBO and ENSO periods. This paper presents new information in the form of diurnal CO analyses, performs useful cross validation among MLS, SABER and WACCM-X T and CO, establishes the role of vertical tracer advection for tides, and reinforces earlier findings of QBO and ENSO variability in the propagating diurnal tide. Publication is therefore recommended following the revisions suggested below.

1. Lines 78-83: Does MLS sample at 2AM and 2PM at all latitudes? A latitude versus local time map might be helpful.

To address this concern, we have added the following sentences: *"Nguyen and Palo (2013) have shown that up to around latitude 50 degrees, the data-points of MLS are at either ~2 AM or ~2 PM local-time. In our work, our calculations show that this can be extended up to latitudes ~80 degrees in both hemispheres although, the number of data-points aren't as much as over the low-latitudes. We make sure to note this in the analysis."*

2. Sections 3 and 4: Figures 2 and 3 are described in exhaustive, almost mindnumbing detail. Instead of listing the altitude and latitude of every positive and negative extremum in each panel, I suggest a more concise wording with the goal of leaving the reader with the following "take-home" messages:

> **a. The structures are dominated by (1,1) in March. A line plot of the (1,1) mode would be useful here.**
>
> **b. WACCM-X DW1 exhibits an additional "pulse" above 90 km in March that is not seen in MLS, both in CO and T, due to either a shorter vertical wavelength in WACCM-X, or to a phase offset between the model and the data.**
>
> **c. Patterns of T and CO are more asymmetric in June than in March. Please lose the "distortion of (1,1)" terminology. (See comment 8 below.)**

We have modified the presentation of figure 2 into:

"Figure 2a shows that in March equinox, the largest MLS CO μ′ are above 80 km and has a latitude structure consistent with the (1,1) mode in temperature; that is, peak positive anomalies of around +6 ppm over the low-latitudes and peak negative anomalies of around -4 ppm over the mid-latitudes (Forbes, 1995; Mukhartov et al, 2009). The peak negative perturbation over the southern mid-latitudes begins at around 87 km and extends above 92 km which is beyond MLS observation range. On the other hand, the peak negative perturbation over the northern mid-latitudes is located between 87 km and 92 km. Figure 2b shows that in March equinox, the largest SD-WACCM-X CO μ′ are also above 80 km and the latitude structure is also consistent with the (1,1) mode in temperature. However, unlike MLS, SD-WACCM-X CO μ′ exhibits two local maximum (hereafter referred to as "pulse") of the (1,1) mode. The first pulse centered at around 87 km and the second pulse appears to be centered above 92 km. The pulses exhibit opposite phases of the (1,1) mode.

Figure 2c shows that in June solstice, the largest MLS CO μ′ perturbations begin at around 85 km and extends beyond 92 km. MLS CO μ′ has peak positive perturbations of around +2 ppm over the low-latitudes with higher values over the northern low-latitudes than over the southern low-latitudes. Over the northern hemisphere, MLS CO μ′ has peak negative perturbations of around -3 ppm extending from latitude 30° N to latitude 50° N. Over the southern hemisphere, the perturbations begin as negative perturbations of around -1 ppm extending from latitude 20° S to latitude 40° S. Then, it alternates between positive and negative perturbations from latitude 40° S to latitude 60° S. Ignoring the features poleward of latitude 40° S, the latitude structure of MLS CO μ′ in June solstice is consistent with the latitude structure of temperature's (1,1) mode "distorted" by the background atmosphere (Forbes, 1995; Mukhartov et al, 2009). By "distorted", we hereafter mean the presence of other diurnal Hough modes.

Figure 2d shows that in June solstice, SD-WACCM-X CO μ' also has a latitude structure consistent with a "distorted" (1,1) mode but unlike MLS, the model exhibits two "pulses" of the distorted (1,1) mode. The first pulse is centred at around 87 km and the second pulse is centred above 92 km. The pulses have opposite phases. In addition, SD-WACCM-X does not simulate the alternating positive and negative perturbations over the winter hemisphere. This could suggest that MLS observes mean-flow changes affecting these structures that aren't simulated in the model."

We have modified the presentation of figure 3 into:

"Figure 3 shows T′ in March equinox and in June solstice as observed by MLS and by SABER and as simulated by SD-WACCM-X (September equinox and December solstice shown in figure A3). Since we are focused on relating this to CO μ′, we focus on features above 80 km where CO μ′ is largest for both seasons. Figure 3a shows that in March equinox, MLS T′ has very similar latitude structure to MLS CO μ′; that is, it is consistent with the (1,1) mode. Figure 3c shows SABER T′ also in March equinox. SABER T′ has peak positive perturbations of around 30K over the equator which are larger than MLS T′'s. This difference may be attributed to aliasing of other tides on MLS T′ particularly the migrating semidiurnal tides. It may also be

attributed to differences in the instruments' vertical resolutions. SABER has a vertical resolution of ~2 km while MLS has a vertical resolution of ~10 km (Remsberg et al., 2008; Livesey et al., 2011). Given that DW1 typically has a vertical wavelength of ~25-30 km, MLS' coarser vertical resolution can substantially reduce the amplitudes. SABER T''s peak negative perturbations over the northern and southern mid-latitudes are both found between 80 km and 90 km unlike MLS T'. This difference may also be attributed to the uneven sampling of MLS over the middle to high latitudes and/or the vertical resolution differences. Both MLS T' and SABER T' exhibit features consistent with the (1,1) mode although there are clear differences in terms of their structure's hemispheric symmetry (Forbes, 1995; Mukhartov et al, 2009). MLS T''s (1,1) mode appears tilted upward because its southern mid-latitude peak appears higher than its northern mid-latitude peak. SABER T''s (1,1) mode's mid-latitude peaks occur in almost the same altitude, but the northern mid-latitude amplitudes are larger than the southern mid-latitude amplitudes. Figure 3e shows that in March equinox, SD-WACCM-X T' has a latitude structure very similar to that of SD-WACCM-X CO μ'.

In March equinox, MLS T' and SABER T' observe only one pulse of the (1,1) mode between 80 km and 92 km while SD-WACCM-X T' simulates almost two pulses. This may be attributed to the model inaccurately simulating DW1's altitudinal variations. On the other hand, MLS T' and SABER T' are different over the mid-latitudes. This shows that the differences between MLS T' and SABER T' over the mid-latitudes may also be attributed to aliasing of the migrating semidiurnal tide into MLS T'.

Figure 3b shows that in June solstice, MLS T' exhibits a latitude structure consistent with the "distorted" (1,1) mode (Forbes, 1995; McLandress, 1997; Mukhartov et al, 2009). It is very similar with MLS CO μ'. One major difference is that the largest values in MLS CO μ' are above 85 km. Figure 3d shows SABER T' also in June solstice. SABER T' also exhibits features consistent with the "distorted" (1,1) mode. These differences between MLS T' and SABER T' over the mid-latitudes may be a result of MLS inadequate sampling causing significant aliasing from other tides. Our approach in calculating the DW1 component with MLS is susceptible to aliasing from the migrating semidiurnal tide (Oberheide et al, 2003). In solstice, the migrating semidiurnal tide is known to be significant over the winter mid-latitudes (Zhang et al, 2006). These may all contribute to the aliasing in MLS T'. Like MLS T', these features are also consistent with the presence of a distorted (1,1) mode. Figure 3f shows that in June solstice, unlike MLS T' and SABER T', SD-WACCM-X T' shows two pulses of the distorted (1,1) mode above 80 km. In June solstice, MLS T' and SABER T' observe only one pulse of the distorted (1,1) mode between 80 km and 92 km while SD-WACCM-X T' simulates almost two pulses. This is like the case in March equinox. This indicates that the model's inaccuracies in simulating DW1's altitudinal variations occur in all seasons."

3. Figures 2 and 3 have a lot of relatively empty space in them, with the interesting features crowded above 85 km. I suggest replotting them with the vertical axis starting at 75 km.
Replotted with the vertical axis starting at 75 km.

4. The chaotic middle and high latitude features in T and CO during winter months probably reflect variations in the zonal mean T and CO, instead of tides.

In line 194, we added this sentence: *"This could suggest that MLS observes mean-flow changes affecting these structures that aren't simulated in the model."*

5. Line 194: Rewrite as "Although the latitude structure of DW! MLS CO μ' and SD-WACCM-X CO μ' have similarities to the DW1 temperature…".

Corrected.

6. Line 196: Rewrite as "…later use this to prove that the DW1 affects CO."

The entire sentence has been changed to: *"Although the latitude structure of DW1 MLS CO μ' and SD-WACCM-X CO μ' have similarities to the DW1 temperature, it has never been proven that the DW1 tide affects CO."*

7. Lines 204 and 224: "aliasing of other tidal components into MLT T' and CO". I suggest being more specific here. Mention aliasing of migrating semidiurnal tides if the asc-desc LT difference is not 12 hours; also, are you thinking of terdiurnal tide leakage?

We specify that the aliasing might be due to the migrating semidiurnal tides.

8. Lines 228-229, 240, 249, 607: These areas of the paper all refer to "distorted" of the (1,1) mode. (1,1) is an immutable eigenmode, characterized by a maximum at the equator, minima around 24N and 24S, and a uniform vertical wavelength of ~27 km. If the global structure of the tide deviates from (1,1) this is not due to "distortion" of (1,1), but the presence of additional Hough modes such as (1,2), (1,-1), etc.

This "distorted" term is first mentioned in the presentation of figure 2c. To clarify, we have added the following sentence: "By "distorted", we mean the presence of other diurnal Hough modes." We recognize that the common approach in other papers analyzing the (1,1) mode is to have placed quotes in the term "distorted".

9. Lines 230-231: The Forbes, McLandress, and Mukhartov papers cited do not discuss any relationship between the tides and the wave-driven residual mean circulation (v*,w*). Do you mean to say "zonally averaged winds"?

Yes. We have changed "winter residual circulation" into "zonally averaged winds".

10. Lines 239: Delete the reference to nonmigrating tides in the aliasing discussion, as they do not alias to the zonal mean or the migrating tides. Nonmigrating tides do not alias into the zonal mean.

Removed.

11. Provide a reference for equation 2. How is the DW1 component of the nonlinear terms defined? Do they arise from the advection of the DW1 components of μ by zonally averaged (u,v,w)? Or is it advection of time-mean μ by the tidal (u,v,w)?

We have cited Brasseur and Solomon (2006) for equation 2. In this analysis, we do not separate the linear and non-linear advection terms. We are just interested in determining the contributions of total zonal advection, meridional advection, vertical advection, eddy diffusion, molecular diffusion, chemical production and chemical loss.

12. Equation 3: This equation and its physical basis needs to be explained. I did not see any obvious analogies with the expressions in Eckermann et al. 1998. Since vertical motion does not appear, I presume it is inferred adiabatically from T' through ¶T/¶t = N2w'. Is this correct? For tidal motions, why does the frequency not appear in equation 3?

We added the following brief derivation of the equation:

"This equation is derived by first linearizing the continuity equation (equation 2). Then, we assume only the vertical advection term is important. Finally, we set all primed variables into the form $e^{i(kx-\sigma t)}$ where k is the zonal wave number and σ is the tidal frequency. This gives us this equation:

$$i(k\bar{u}-\sigma)\mu_w' + \frac{\partial\bar{\mu}}{\partial z}w' = 0 \qquad (4)$$

The same can be done to a form of the thermodynamic equation that assumes all temperature changes are due to adiabatic motion. This gives us this equation:

$$i(k\bar{u}-\sigma)T' + Sw' = 0 \qquad (5)$$

Combining equations 4 and 5 give equation 3."

13. Lines 307-322. This section is much too wordy and repetitive. Since the vertical gradient of time mean μ is positive in the upper mesosphere (as seen in Figure 1), we don't need to read through hypothetical negative time-mean gradient scenarios. This entire segment can be summarized as: "Equation 3 indicates that when the vertical gradient of the time-mean zonal mean μ is positive, then an increase in μ' requires T' > 0, which under adiabatic conditions implies a net downwelling. Conversely, a decrease in μ' implies T < 0', and net adiabatic upwelling."

We've reduced these paragraphs into the following: *"Equation 3 indicates that if vertical advection does primarily drive a tracer's DW1 component and since figure 1 has shown that zonal-mean CO's vertical gradient is positive, CO μ' and T' are correlated. This also indicates that an increase in μ' requires T' > 0, which under adiabatic conditions implies a net downwelling. Conversely, a decrease in μ' implies T < 0', and net adiabatic upwelling."*

Line 327 and 330: Replace "good" with "positive".

Replaced.

Lines 331-333: "For both MLS CO μ' and SD-WACCM-X CO μ', figures 4c and 4d indicate that the positive perturbations are driven by a relative downwelling due to the DW1 tide while the negative perturbations are driven by a relative upwelling." Since we are not shown either w or ¶u/¶z, there is no way to deduce vertical motion information from anything in Figure 4. Either show these variables, or remove this sentence.

Yes, we are aware that we cannot deduce the exact or absolute vertical motion. Hence, we use term "relative".

14. Lines 372, 416, 417, and page: Replace "regress" with "project". "We project the latitude profiles of CO μ′ onto the (1,1) Hough mode profile.

Replaced.

15. Line 407: "Figures 6a and 6b showed MLS CO h′ is weaker than SDWACCM-X CO h′. Actually, MLS looks stronger than WACCM-X to me.

Corrected.

16. Figures 7a-c and 8a-c are difficult to read in general, and certainly for more nuanced features such as "Above 90 km, their seasonality shifts into having a primary peak close to June solstice". I recommend staring the vertical axis at 75 or 80 km, or presenting the main features as line plots at selected representative altitudes.

We have adjusted the vertical axis to begin at 75 km.

17. Lines 480, 511, 513: CO h′ increases…" What are the units of Figures 9c-f? Amplitude? Correlation? What aspects of h' and hμ "increase"

We clarify that the units of all cross-wavelet spectrum are in spectral power by adding the following line: *"In this and the succeeding spectra, encircled regions with the high spectral power correspond to oscillations statistically significant in both time-series (Grinsted et al, 2004)."*

To clarify what aspects of h'_μ increases or decreases, we add the following in lines 490: *"Depending on the arrows, one can deduce the correlations between CO h'_μ amplitude and QBO or ENSO. Consequently, the deduced correlation will imply whether CO h'_μ increases or decreases during, for example, westerly QBO phase."*

18. Line 493: Change "of temperature" to "tide".

Changed.

19. Line 514: "Most studies have found that the (1,1) mode should decrease during El Nino events". In fact, Lieberman et al. (2007) showed that (1,1) increased during ENSO events. The reason is that the climatological dry tongue disappears during the El Nino phase, leading to a more longitudinally uniform water vapor distribution, and therefore a stronger (1,1) forcing by water vapor heating.

We have modified this section to also include this suggested explanation: *"Most studies have found that the (1,1) mode should decrease during El Nino events. However, our results indicate that the effect of ENSO reversed during the 2015 El Nino. Kogure et al (2021) has explained this. Their work showed that the enhanced (1,1) tide in 2015 was a result of the overlapping occurrence of an easterly QBO phase and an El Nino event. Lieberman et al. (2007) also showed that the (1,1) mode increased during ENSO events because the climatological dry tongue disappears during the El Nino phase, leading to a more longitudinally uniform water vapor distribution, and therefore a stronger (1,1) forcing by water vapor heating. Our works adds to these previous studies by showing that MLS CO's (1,1) mode is also affected by ENSO in the same way."*

20. Section 7: The Summary is much too long, and repeats details that were already worked over in the main body of the paper. The entire section can be condensed to: "This work uses 17 years of CO observations provided by the Microwave Limb Sounder (MLS) on-board the Aura satellite to analyse the seasonal and interannual variability of the DW1 component of upper mesospheric CO. These were then compared to simulations by the Specified Dynamics – Whole Atmosphere Community Climate Model with Ionosphere/Thermosphere eXtension (SD-WACCM-X). CO DW1 is dominated by the (1,1) mode in both MLS data and WACCM-X. However, MLS only observes one pulse of the (1,1) mode between 80 km and 95 km while SD-WACCM-X simulates two pulses. This could be due to MLS' limited vertical resolution, or it could be due to inaccuracies in SD-WACCM- X simulation of the background atmosphere and/or tidal vertical propagation. The model-data comparison revealed that the structure of upper mesospheric MLS CO's DW1 component is primarily driven by DW1-induced vertical advection over all latitudes during equinox seasons, and over all latitudes except the winter middle to high latitudes during solstice seasons. This could suggest that MLS CO's DW1 component over the winter middle to high latitudes may be driven by other mechanisms such as meridional advection, eddy diffusion and/or chemistry. It could also suggest that the data over the winter middle to high latitudes may be affected by inadequate sampling. In addition, we find that the interannual variability of MLS CO (1,1) and SDWACCM-X CO (1,1) is primarily driven by the QBO and ENSO's effects on DW1- induced vertical advection. These conclusions suggest that we can use CO as a tracer for vertical advection due to the DW1 tide and the (1,1) mode on seasonal and interannual timescales. "

We have reduced the summary as follows:

"This work uses 17 years of CO observations provided by the Microwave Limb Sounder (MLS) on-board the Aura satellite to analyse the seasonal and interannual variability of the DW1 component of upper mesospheric CO. These were then compared to simulations by the Specified Dynamics – Whole Atmosphere Community Climate Model with Ionosphere/Thermosphere eXtension (SD-WACCM-X). Our results showed that the largest MLS CO μ' and SD-WACCM-X CO μ' are above 80 km. For MLS CO μ', its latitude structure in March equinox above 80 km resembles that of the (1,1) mode although there is an interhemispheric asymmetry with the location of their mid-latitude peaks. On the other hand, the latitude structure of MLS CO μ' in June solstice above 80 km resembles that of the "distorted" (1,1) mode. For SD-WACCM-X CO μ', it's latitude structure in March equinox above 80 km also resembles that of the (1,1) mode but there is negligible interhemispheric asymmetry with the location of their mid-latitude peaks. Also, SD-WACCM-X simulates two pulses of this (1,1) mode feature between 80 km and 95 km while MLS observes only one pulse. SD-WACCM-X CO μ' in June solstice also resembles that of the "distorted" (1,1) mode but SD-WACCM-X simulates two pulses of this mode.

To explain MLS CO μ' and SD-WACCM-X CO μ', we first looked at MLS T', SABER T' and SD-WACCM-X T'. All three show the (1,1) mode in March equinox and the "distorted" (1,1) mode in June solstice. However, the (1,1) mode in March equinox for MLS T' shows more interhemispheric asymmetry in terms of the locations of the mid-latitude peaks. Also, SD-

WACCM-X T' showed two pulses of the (1,1) mode and "distorted" (1,1) mode. These gave hints that the mechanisms driving CO μ' may indeed be related to the mechanisms behind T'.

To determine what drives CO μ' and how it relates to T', we first did a tendency analysis involving the continuity equation. Our tendency analysis revealed that, in SD-WACCM-X, vertical advection in both March equinox and June solstice has the closest magnitude and latitude-altitude structure to the time-derivative term. We then determined if the same mechanism holds for the observations by using the adiabatic displacement method. Our adiabatic displacement method determined that for March equinox, CO μ' and CO μ'_w in observations and simulations were very similar. However, for June solstice, MLS CO μ' and CO μ'_w are only similar between latitudes 30° S and 60° N. The simulations were very similar for all latitudes

After comparing CO μ' and CO μ'_w in observations and simulations, we probed deeper into CO's (1,1) mode. Our results showed that for seasonal and interannual timescales, the observed and simulated CO h'_μ and CO h'_w are highly correlated with correlation coefficients of at least 0.97.

Finally, we characterized the interannual variability present in CO μ'. A cross-wavelet, MLR analysis and lowpass filtering indicate that MLS CO h'_μ is enhanced by around 8% during the westerly phase of the QBO and is reduced by around 16% during the easterly phase of the QBO. SD-WACCM-X CO h'_μ is also enhanced by around 10% during the westerly phase of the QBO and is also reduced by around 20% during the easterly phase of the QBO.

A cross-wavelet between MLS CO h'_μ at ~90 km and the ENSO index shows that MLS CO h'_μ and ENSO index both have statistically significant oscillations with periods of around ~30 months between years 2008 and 2012. This coincides with the strong 2010-2011 La Nina event. On the other hand, a cross-wavelet between SD-WACCM-X CO h'_μ at ~92 km and the ENSO index shows that SD-WACCM-X CO h'_μ and ENSO index both have statistically significant oscillations with periods between 24 to 36 months from 2006 till 2016. This coincides with both the strong 2010-2011 La Nina event and the strong 2015-2016 El Nino event. However, the lack of ENSO events indicate that these may just be coincidental.

From these results, we can conclude that the global structure of upper mesospheric MLS CO's DW1 component is primarily driven by DW1-induced vertical advection over all latitudes during equinox seasons and over all latitudes except the winter middle to high latitudes during solstice seasons. On the other hand, the global structure of upper mesospheric SD-WACCM-X CO's DW1 component is primarily driven by DW1-induced vertical advection over all latitudes for both equinox and solstice seasons. We also conclude that the dominant DW1 tidal mode in upper mesospheric MLS CO DW1 and SD-WACCM-X CO DW1 is the (1,1) mode. In addition, we find that the interannual variability of MLS CO (1,1) and SD-WACCM-X CO (1,1) is primarily driven by the QBO and ENSO's effects on DW1-induced vertical advection. These conclusions suggest that we can use CO as a tracer for vertical advection due to the DW1 tide and the (1,1) mode on seasonal and interannual timescales."

Grammar and style:

1. Line 40: New paragraph at "While".

Corrected.

2. Line 97: New paragraph at "Model".

Corrected.

3. Pages 11-12 are a bit too verbose. Consider deleting line 302 (If CO μ' and CO μ' are similar, then we can argue that vertical advection does primarily drive CO μ') and lines 308-312 (Equation 2 indicates…)

As mentioned in major comment #13 above, we've reduced these paragraphs into the following: *"Equation 3 indicates that if vertical advection does primarily drive a tracer's DW1 component and since figure 1 has shown that zonal-mean CO's vertical gradient is positive, CO μ' and T' are correlated. This also indicates that an increase in μ' requires $T' > 0$, which under adiabatic conditions implies a net downwelling. Conversely, a decrease in μ' implies $T < 0'$, and net adiabatic upwelling."*

4. Line 370-371: Rewrite as "In this section, we examine seasonal and interannual variations in the (1,1) mode of CO."

This suggested replacement oversimplifies what we intend to do in this section but we do reduce it into: *"In this section, we now focusing on determining vertical advection's impact on the seasonal and interannual variabilities of CO's (1,1) mode."*

5. Line 378: New paragraph at "Figure 6".

Corrected.

6. Line 446-459: "For example, Smith et al (2010) proved… very similar but for mesospheric SABER water vapor." Delete, unnecessary verbiage.

Removed.

7. Line 477: New paragraph at "Figure 9".

Corrected.

8. Line 565: New paragraph at "Figure 10b".

Corrected.