Point-to-point response to Reviewer 1:

Thank you very much for your careful review comments and corrections! I performed a moderate revision.

Your points are in bold face, *our response is in italic font style*, the changed text is in a normal font style.

1) The findings are of interest to the scientific community. However, I believe ACP may not be the most suitable journal for this type of paper, and I would suggest considering submission to Annales Geophysicae (or similar) instead.

Thank you. ACP is suitable in so far as this journal has editors for the middle atmosphere. The satellite experiment Aura/MLS is often mentioned in ACP so that the readership of ACP will be interested in the article. I agree that Annales Geophysicae also would be suitable.

2) Line 11. Please consider using "thermal tides" instead of "solar tides". Technically speaking, solar tides can still be gravitational, so using the word "thermal" makes the distinction clear.

This is true. I will use "solar thermal tides" in the revised manuscript.

3) Lines 20-21. This sentence needs to be revised. The amplification of the lunar tide at MLT altitudes is typically observed during major sudden stratospheric warmings (SSWs) that are accompanied by a strong polar night jet oscillation (PJO). In contrast, the lunar tide observed during winters with major SSWs but without strong PJOs appears very similar to that of winters with no major warmings. For example, see: https://doi.org/10.1029/2019JD030828

Thank you, I didn't know that. Now, I mention that the PJO is important for the amplification of the lunar tide.

[1] emphasized that the lunar tide is only amplified during SSWs that are accompanied by strong polar night jet oscillations (PJO).

4) Lines 41-42. The phrasing here is a bit confusing to me. Why would a "more standing" wave have a smaller amplitude compared to a "more propagating" wave? Besides, what does "more propagating" really mean in this context? Did you mean "less dissipated"? Please clarify this.

Okay. The phrasing was overtaken from the paper of Geller (1970) [2]. It refers to the tilt of the phase front. "more standing wave" means a larger ver-

tical wavelength or a more perpendicular tilt of the phase front. I will clarify it in the revised manuscript.

This amplitude variation is due to a change of the vertical thermal structure which favors a more propagating wave (smaller vertical wavelength) in January and a more standing wave (larger vertical wavelength) in July.

5) Lines 59-60. Could it be that the reason of a not so clear M2 signature in the temperature measurements is partly due to previously reported issues with Aura/MLS temperature measurements? The studies by Wing et al. (2018) and Marlon et al. (2021) show, e.g., that MLS has a seasonal and altitude dependant bias in temperature compared to SABER and lidar.

I think the lunar tide in temperature is rather small at 82km height (Figure 5). Thus, it is difficult to get a clear spectral peak in the spectra at 82km. The lunar tide signal would be clearer if I would show the spectrum at 90km height or at 94km, the highest level of Aura/MLS. For unknown reasons, the lunar tide in geopotential height is already clear and dominant at 82km height. However, I would not say that the lunar tide in temperature has an error, since the observed magnitude is similar to that of TIMED/SABER measurements.

6) Line 78. Please consider removing the "I like". You can simply write, "Firstly, to avoid errors due to the interpolation."

Thank you. I agree.

7) Line 90. How does Aura/MLS actually measure the lunar tide? How often does the satellite observe the same geographic location again? My understanding is that the ground track repeats about 15-16 days.

Aura/MLS provides at a fixed location two profiles each day. One profile around noon and one profile around midnight. This is due to the Sun-synchronous orbit of Aura.

8) Has the author attempted to use the longitudinal structure of the observations to extract the zonal wavenumber of the signal? This could be a useful diagnostic. The dominant semidiurnal lunar tide should appear primarily as a zonal wavenumber 2, which would help to confirm that the observed $\sim$ 14-day modulation is indeed related to the lunar tide.
At the same time, could aliasing associated with the "xed local-time sampling of the satellite lead to mixing with other apparent zonal components (e.g., wavenumbers 1 or 3)? A discussion of this issue would be helpful.

I tried to explain with the scheme in Figure 1 that Aura/MLS can only measure the lunar tidal bulges when they cross tha orbit plane of Aura. This is always the case after an half lunar month. The situation of Aura is very different to a ground station which can sample the lunar tide in longitude because the ground station rotates each day through the lunar tidal bulges. The data analysis which I selected emphasizes the M2 tide since the M2 tide appears with the same phase on the day- and night side of the Aura orbit. A wave with a different wavenumber (not 2) would not have the same phase in the day and night measurement of Aura/MLS. I added two sentences about this topic at the end of section 2.1

The selected data analysis favours the detection of the M_2 tide in the Aura/MLS data since the M_2 tide appears with the same phase in the noon and midnight observations of Aura/MLS. Thus, the dominant lunar tidal perturbation with zonal wavenumber 2 remains in place in the average of the noon and midnight data of Aura at a given location.

9) Line 106. Please be careful with the wording. Zero padding does not enhance frequency resolution, but rather increases FFT sample density, which results in a better definition of the peaks, but not a higher resolution. And, are there any gaps in the data? If so, how were they handled?

I agree, it is better to use the term FFT sample density. There are only a few data gaps in the Aura/MLS series. However, if a day is missing , I use linear interpolation.

The FFT frequency sample density is enhanced by zero padding where we add about 17 years of zeros before and after the time series subtracted by its mean value. The relative proportion of data gaps in the 17 years of Aura/MLS observations is only 1%, and these gaps were closed by linear interpolation.

10) Line 107. Instead of "at the left and at the right", I would rather write "before and after".

Done.

11) Lines 113-121. I found this paragraph somewhat difficult to follow and had to read it more than once to fully understand the data processing procedure. I get the main workflow: apply FFT to the entire time series to identify the lunar peak. Then, apply a band pass filter around the M2 peak and reconstruct the amplitude envelope to track the seasonal variability of the lunar tide. However, this part could benefit from a slightly more detailed description of the steps involved. Expanding it a bit would likely make the procedure easier to follow, particularly for readers with less experience in signal pro-

cessing, and would help them implement the approach more easily.

Thank you. Your understanding is correct. I re-checked the description and made it clearer with some adds and rearrangements.

12) Line 123. Was the FFT applied to the geopotential heights or to the geopotential height perturbations? In line 107, the author mentions that a mean was subtracted from the dataset, so I am a bit confused. Please make this clear.

Thank you, I write now that the FFT amplitude spectra of the oscillations of GPH (or T) are computed.

13) Lines 150-151. How close a value of 0.02 K is to the precision limit of the temperature measurements? In line 84, it is mentioned that the precision in the stratosphere is 1 K. I guess the number of samples considerably reduces the 1 K sigma, so there's no need to worry about the precision. But, is this 1 K precision really only measurement noise, or does it also include geophysical variability? This distinction could affect how confidently such a small signal (0.02 K) can be detected.

The precision characterizes the instrumental noise. Since the study is using 17 years of data and averages of latitudinal belts, the error of the mean (precision divided by square root of the number of atmospheric profiles) is much smaller than the 1K of the precision. However, at stratospheric heights, the spectral peak of the lunar tide disappears in the atmospheric noise background. In this case, the amplitude of the atmospheric noise background can serve as an upper boundary value for the lunar tide. I added these informations in the revised manuscript

14) Line 155. The author mentions that the vertical wavelength of the lunar tide is roughly 500 km in the mesosphere. Is that correct? 500 km? Could the author please describe how this number was determined? From Figure 6, I can estimate a value close to 290 km at the steepest parts of the profile, but it's not clear how a value of 500 km would be obtained.

For example, in case of the red line : the phase at 94 km is 170 deg and at 64 km it is 145 deg. Then $\frac{\lambda_z}{94km-64km} = \frac{360^\circ}{170^\circ-145^\circ} \rightarrow \lambda_z = 432km$ *. So, I think 500 km is a good estimate.*

15) Line 159. Could you please make Figure 7 wider? And also add more ticks in the x-axis? This will make the differences between January and July easier to identify.

Yes, I enlarged the figure 7 time series plot now in the revised manuscript. I think you can easily distinguish between July and January since the January 1 is always on the vertical grid line, and July 1 is between two vertical grid lines.

16) Line 169. Would it be possible to add a sketch depicting Geller's Figure 10? Having access to a paper from 1970 is not that straightforward, and the Doi provided in the references does not work.

Sorry, that you had trouble with the egusphere doi-link of Geller's paper. I checked it and in my case the link of my egusphere pdf article works. However you could search with Google for the title of Geller's paper. Then you come quickly to the pdf file of Geller's article provided in open access by the Journal of the Atmospheric Sciences. I think this journal is excellent in providing the old articles without any fee.

17) Line 172. Did the author do a similar analysis separating years with strong PJOs (or at least major SSWs) from those without? That would certainly help to determine if the enhancement of the lunar tide is due to SSWs.

No, I didn't know about the importance of strong PJOs for the amplification of the lunar tide. I will keep such a classification in mind for future studies.

18) Line 173. Could the author please provide more details on how the climatology was determined? Additionally, as suggested in the previous point, comparing a climatology of years with major SSWs to one of years without could help assess the impact of these events on the lunar tide.

Thank you, I added a sentence for explanation of the seasonal variation (climatology). The 17 years might be not long enough for statistics of years with SSW and PJO and years without.

The seasonal variation is obtained by bandpass-filtering of the time series at the period of a half lunar month and by sorting the 17 years-long amplitude envelope as function of Day of Year.

19) Line 187. Please change "geopotent" by "geopotential"

Thank you! Done.

20) Line 197. Please change "showed that the lunar tide in is more amplified" by "showed that the lunar tide is more amplified".

Thank you. Done.

21) Line 204. Please change "geopotantial" by "geopotential".

Thank you. Done.

22) Line 212. Several studies have investigated the lunar tide during the northern hemisphere's winter. However, citing only one, which is 20 years old, presents a limited perspective. For example, more recent works such as Chau et al. (2015), Siddiqui et al. (2015), Conte et al. (2017), Conte et al. (2019) offer additional insights.

Okay, I added three of the four references.

23) Line 215. The fact that the lunar tide is stronger in January than in July is one of the main points raised in several parts of the article, but it is discussed very briefly. It would be helpful if a few more sentences were devoted to discussing this point.

I think the reader can take the theoretical explanations from the Geller article which I indicated in the next sentence. As I understood, the change of the vertical temperature profile explains the difference of the lunar tidal amplitude between January and July. I add one sentence about Pekeris resonance.

A change in the temperature profile can shift the resonance period of the atmosphere to the frequency of the lunar tide, so that an amplification of the lunar tide occurs [3, 4].

24) Line 220. "The observed mean lunar tide is up to 55m (geopotential height amplitude) in the mesosphere while the simulation shows amplitudes between 99m in July and 220m in January at 90km height". How should this be interpreted? Most of the results in this paper are presented at 82 km of height. Figure 4 shows a vertical pro"le of the lunar tide in geopotential height but over the entire time series, without discriminating between January and July. And Figure 7 displays the lunar tide as a function of time, but at 82 km altitude.

yes , the observations indicate a mean value of 55 m while the simulation is around 160m in average. I add further sentences.

Thus, the observed amplitude is in average about three times smaller than predicted by the simulation. It can be that the boundary conditions and the vertical thermal structure of the model atmosphere have to be adjusted for a better agreement.

Thank you for your review!

Point-to-point response to Reviewer 2:

Thank you very much for your careful review comments and corrections! I performed a moderate revision.

Your points are in bold face, *our response is in italic font style*, the changed text is in a normal font style.

1) Line 43-48 - The manuscript refers to the (2,2) and (2,4) modes of the lunar tide, but these are not really defined for the reader. Since the later interpretation of the phase profiles also relies on this terminology, a brief explanation of what these mode labels mean and why they are relevant here would help the reader follow the later discussion.

I agree and I add an explanation of the tidal wave mode (m,n).

(2,2) refers to the tidal wave mode (m,n) where m is the zonal wave number and n is the meridional mode number. The latitude structure is described by the Hough function with n−m internal nodes where the tidal amplitude is zero. The (2,2) mode is symmetric with a maximum of the tidal amplitude at the equator and a decrease of the amplitude towards the poles. While the (2,2) mode propagates vertically with a long wavelength of about 300km, the (2,4) mode has a shorter vertical wavelength.

2) Line 90 - The most important issue in the paper is the explanation of how the semidiurnal lunar M2 tide appears as a semi-monthly signature in Aura/MLS because of the sun-synchronous sampling. This is central to the interpretation of the entire analysis but is currently explained mostly qualitatively. Since the analysis relies on the 14.7653-day signal as the observational signature of M2, it would improve the paper if the authors could include a clearer explanation, or a short mathematical derivation, of this sampling/aliasing framework.

I agree and I added a formula for the aliasing frequency in Figure 1.

The aliasing frequency f_{alias} is defined as $f_{alias} = f_{tidal\ bulge} - f_{Aura}$. In the Sun-fixed coordinate system of Figure 1 the green line of the Aura orbit is fixed (no azimuthal rotation) so that $f_{Aura} = 0$. The frequency of the tidal bulge $f_{tidal\ bulge}$ in the Sun-fixed coordinate system is 2/(lunar month). Thus, the aliasing frequency is equal to 2/(lunar month). The corresponding aliasing period of the lunar tide in the Aura dataset is $T_{alias} = \text{(lunar month)}/2 = 14.7653$ days.

3) Line 104-105 - The text states "the arithmetic mean of all observed atmospheric profiles is computed" each day, but Aura samples

each latitude twice per orbit at two fixed local solar times (01:45 and 13:45 LST at the equator). This daily mean combines sampled from both Aura local-time branches. Since the two overpasses are separated by about 12 hours, this works for the semidiurnal tide because the two samples are nearly in phase for a 12.42-hour oscillation. Could the authors state this explicitly in the methodology, since this seems important for justifying the daily averaging procedure used to construct the time series?

I agree and I add an explanation. It is important that the lunar tide has a zonal wavenumber 2, so that the daily average of the noon and midnight profiles contain the full tidal signal.

The local time of the atmospheric profiles is either around noon or midnight. Since the lunar tide has a zonal wavenumber 2, the tidal bulges will appear similarly in both, in the atmospheric profile at noon and at midnight. Thus, the lunar tide is fully contained in the daily means of the selected atmospheric profiles.

4) Line 137 - 148 - Line 137 - 148 The manuscript does show January-versus-July variability for Aura/MLS at 82 km in Figure 7. However, the vertical-profile comparison with Geller (1970) in Figures 4 and 5 seems to be compared with the full-record Aura/MLS amplitudes, whereas the values from Geller are for January and July. Since the Aura/MLS data also show a pronounced January-July difference in Figure 7, it would help if the authors could clarify how the full-record Aura/MLS amplitudes in Figures 4 and 5 should be compared with the January and July values from Geller (1970).

Yes, I should add a sentence which explains the imperfectness of the comparison.

I assumed here that the mean of the January and July value of the z amplitude from [2] can be roughly compared to the annual mean of the z amplitude from Aura/MLS.

5) Line 172-179 and 206-215 - Figures 8 and 9 show enhanced amplitudes at high latitudes in winter, and the discussion relates this to radar observations and possible SSW-related amplification. At the same time, the manuscript also states that contamination by planetary wave-like oscillations cannot be excluded. Could the authors comment on how much contamination from other variability is expected at high latitudes in winter, and whether the signal seen at high latitudes in Figure 9 can still be confidently interpreted as a lunar tide signature?

I have not the experience to make an estimate of the contamination in Figure 9 from various sources. Generally, it seems to be a problem to retrieve tidal parameters at high latitudes from satellite observations. I am critical about the high values of the lunar tide at northern polar latitudes in winter (Figure 9) since the annual mean of the lunar tide (Figure 8) only shows small values of about 15m for the lunar tide at northern polar latitudes. I will mention this uncertainty of Figure 9.

In addition, the annual mean of the lunar tide in Figure 8 is just around 15m at northern polar latitudes. This seems to be not consistent with the large tidal amplitude values (up to 148m) at northern polar latitudes in winter in Figure 9. The retrieval of the annual mean of the lunar tide is certainly more reliable than the retrieval of the monthly means of the lunar tide, since the lunar tide signal can be better separated from atmospheric noise in case of the FFT of the whole time series (Figure 8).

6) Line 74 - The authors mention the vertical range of the atmospheric profiles between 15 to 95 km and then note on line 86 that 'The temperature and geopotential height values beyond 90 km altitude are less reliable'. However, it is not explicitly whether the analysis will be limited below 90 km. The vertical profiles in Figures 4 and 6 appear to slightly extend over 90 km, and the text describes the upper limit for these figures at 90.4 km. A simple line stating the altitude or pressure range used in the analysis will improve the clarity for the reader.

Yes, I see this weakness in the vertical range description. I removed the sentence " .... beyond 90 km less reliable" since I have no indication for this statement.

7) Line 77 - Could the authors briefly explain how the interpolation errors would affect the analysis or results? i.e. would the method used here affect the retrieved amplitudes and phases?

I think an explanation is not necessary since the data were not interpolated to fixed height levels. Other studies show that such an interpolation is feasible, that means, the error is possibly small.

8) Line 177 - Please provide citations for the "numerous reports"

This result is in agreement with numerous reports on the lunar tide and the geomagnetic lunar tide which is stronger in January than in July [5, 6, 7, 4, 8, 1].

Thank you for your careful review which improved the manuscript (and also for detection of typos).

References

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