# Response to referee#2's comments for manuscript

We'd like to thank the Reviewer for his/her positive feedback and valuable comments. Here we clarify the comments of the Reviewer, with his/her comments in black and our responses indented in blue.

The authors would like to thank the substantial comments and suggestions from the referees, which significantly helped improve the quality of this manuscript. We have revised the manuscript carefully based on the comments and suggestions of the reviewer. More details of the revision can be found in the revised manuscript as well as the point-to-point response as follows (all authors' responses here are in blue). However, to clarify the results we introduced the following changes:

- a case study comparing WACCM-X(SD) and all observations plus MERRA2
- all Figures are now provided in altitude
- we added sections comparing ozone and water vapor with WACCM-X(SD)
- identical tidal analysis for WACCM-X(SD) and meteor radars

The study by Shi et al utilized observational data of winds, ozone and water vapor at high northern latitudes to analyze the response of tidal wind amplitudes to sudden stratospheric warmings (SSWs), and ask the question whether anomalies in radiative active trace gas abundances may contribute to the anomalies in tides. Global model data are used to deduce anomalies in radiative heating rates before, during and after SSWs. The study presents interesting signals in tidal amplitudes of the diurnal, semi-diurnal and terdiurnal tides at three different latitudes. Furthermore, trace gas anomalies (water vapour and ozone) associated with SSWs are shown to be very consistent between satellite data (MLS), global model simulations (WACCM-X) and local measurements in Svalbard, which is a very encouraging result. The consistent and comprehensive quantification of tidal and trace gas anomalies around SSWs from observational data is a valuable set of analysis worth publication. The study further puts forward the suggestion that the trace gas anomalies are important in "explaining the observed tidal variability during SSW events" (abstract, line 19-20). While I agree that the modification of tides by ozone anomalies is a plausible mechanism, I have to disagree that the pieces of analysis shown in the study provide any quantification of this radiative effect, as detailed below. It is a valid and interesting point to discuss the possible impact of the trace gas anomalies (and associated heating anomalies diagnosed from the model) on the tidal anomalies, but the authors should present those points as discussion of possible (!) effects, rather than stating that a comprehensive explanation of tidal variability is obtained in the study. Furthermore, there are a number of corrections necessary in to improve the presentation of the results, and at a few places I found the description of the results inconsistent. Overall, I recommenced that the authors revise their manuscript majorly, focusing the study on the quantification of SSW signatures in tides and tracers.

**Major comments:**

1) Quantification of role of trace gas anomalies to force tidal anomalies

The authors state that they "presents the first comprehensive attempt to explain mesospheric tidal variability ..." (line 306, similar in abstract line 19-22). As stated above, I generally agree that the study presents an interesting and comprehensive quantification of tidal variability and co-located tracer variability from observational data, and it is valid to discuss whether there could be possible effect of tracer anomalies on tidal variability. However, I have to disagree that the study is a comprehensive attempt to explain the tidal variability, for which an actual quantification of the role of trace gas anomalies for the tidal generation would be necessary.

While the presentation of the radiative heating rates from model data help to infer whether there might be an effect at all from the tracer anomalies, this is not sufficient to conclude on whether the tracer anomalies actually play a role to cause the tidal anomalies. For this, as least two more steps would be necessary: a) quantify how much of the radiative anomaly is actually due to the tracer anomalies; b) quantify how much the anomalous radiative heating/cooling contributes to tidal generation. The former could be done by offline radiative calculations. A full quantification would, as far as I can see, only be possible by conducting model simulations which either include or discard the tracer anomalies. As of now, the statements made in the paper on the role of tracer anomalies for tidal variability are at most based on scaling arguments (e.g., role of tracer anomalies for heating, see comment on lines 257-259; argument about similar strength of relative anomalies in line 365-366), and many very speculative statements are made in particular on the relative role of anomalous heating/cooling via tracer anomalies versus anomalous propagation due to changed background winds (e.g., on page 15, see individual comments below on line 257-259, line 284, 286).

I understand that conducting simulations for the actual quantification would go beyond the scope of the paper. Therefore, I suggest that the authors focus on the quantification of the tidal and tracer anomalies from observations, which by itself composes an interesting set of analysis. This can be complemented by a discussion of possible effects of the tracer anomalies on tides, but making sure to emphasize the uncertainties and the speculative nature of some of the arguments/hypothesis put forward.

We appreciate this detailed feedback and valuable comments regarding the quantification of the role of trace gas anomalies in tidal variability.

a) We have reconstructed the structure of this manuscript, presenting an interesting and comprehensive quantification of tidal variability and co-located tracer variability from observational data, and discussing the possible effect of tracer anomalies on tidal variability.

b) We added a case study to show the heating rate variation, which reveals a clear signature of a diurnal forcing starting 20-30 days after the SSW. The heating rate is mainly contributed by the absorption of UV radiation by ozone in the stratosphere and in the lower mesosphere. Therefore, we clarified that the radiative heating rate from ozone plays an important role in the DT amplitude enhancement.

c) WACCM-X(SD) tides are generated by the interactive chemistry and, thus, by the radiative forcing. Water vapor and ozone are presented as proxies for the total balance. The nudging at the lower boundary might also prescribe part of the tides at the stratosphere, however, as shown in the case study a few kilometers above the nudging altitude the WACCM-X(SD) GW parameterizations dominate the dynamics and the radiative forcing from the chemistry provides a key sources for the tidal forcing.

2) Inconsistencies in the discussion on SDT

Much of the discussion on the effects of ozone anomalies on tides focuses on STD, which was shown to be enhanced just around the central date of SSWs. I have to admit that I got confused about the timing of when this link is suggested to act. At places, it is stated that the STD enhancement is linked to the persistent ozone (and associated QRS) anomaly over several weeks after the SSW (e.g., in line 253), but this is inconsistent with the timing of the STD anomaly just around the SSW event. At other places, the STD enhancement is stated to occur at the SSW onset, and that it is "... attributed to zonal wind changes and ozone heating at mid- to low latitudes" (line 311). Firstly, there is no actual attribution presented in this study (see major comment 1 above), and secondly ozone heating at low- to mid-latitudes is not shown here, so this confuses me even further. Please ensure to clarify better the proposed link between ozone anomalies and STD anomalies (see also individual comments below on line 253, 311, 315, 329)

We have added one chapter to illustrate the water vapor, ozone, and radiative effects, linked to the SDT amplitude. WACCM-X(SD) simulation shows the primary stratospheric ozone layer at 20-50 km, the tertiary ozone layer around 60-70 km, and the secondary ozone layer above 90 km. We have clarified that this double-layer structure (stratospheric ozone layer and secondary ozone layer) is mainly responsible for the semidiurnal tidal activity during the winter months at these latitudes. The superposition of the in-situ forced tide at the secondary ozone layer is out of phase with the stratospheric tide excited around 50-60 km altitude that needs to propagate upward 30-50 km. This coincides with the vertical wavelengths that are found in climatological analysis (Stober et al., 2021b) for these stations. During the SSW, this balance is disturbed, and the secondary ozone layer together with the elevated stratopause provides favorable conditions to amplify the SDT. The QRS shows a pronounced enhancement that coincides with the time of the semidiurnal tidal amplification.

Additionally, we analyzed observations from the southernmost Meteor Radar (51.3N) available in the European sector, located at the edge of the polar vortex and, which sometimes shows signs of SSW events (see Appendix B). As a result, the derived mean winds and tidal anomalies show a morphology similar to that observed at polar and high latitudes. In particular, the enhancement of SDT remains evident. A few degrees further south, observations from MIAWARA and GROMOS provide additional insights. The water vapor and ozone VMR for the location at Zimmerwald/Bern (47N), Switzerland. Performing the same epoch analysis used for GROMOS-C and MIAWARA-C exhibits no longer a signature of the SSW events. This is also reflected in the QRL and QRS anomalies shown in Appendix B. The QRL and QRS cooling and heating rates indicate a more stratified vertical structure resembling the layering found in the trace gas measurements at the stratosphere and lower mesosphere.

3) Methodological issues and presentation of results

- Some methodological clarifications are needed, e.g. stating more clearly which time periods are used for the different data sets and clarifying some details on how the tides were fitted and how the (relative?) anomalies were calculated. See individual comments below.

We have more clearly stated the time periods used for the different data sets and elaborated on the fitting process for the tides. We also have clarified the details of how the (relative) anomalies were calculated.

**Individual comments:**

Title: I suggest to revise the title; in its present form there might be a word missing ("the polar ozone and water vapour ANOMALIES (?)"), and the "radiative effects" in the middle of the title seems out of place. Also, is "polar" referring to everything, or just ozone (as it appears right now)? How about simplifying the title to something like "Response of tides in the polar MLT to SSW events, and their link to ozone and water vapour anomalies."

All stations used in the current study are located north of the polar circle and, thus, we plan to keep the term polar in the title. Furthermore, we present more details leveraging WACCM-X(SD) fields at a sub-daily resolution to visualize the diurnal effects of short-wave absorption and ozone chemistry. We also provide similar viewgraphs for water vapor, although less relevant for the direct tidal excitation. The QRL is mainly contributing to the background wind and temperature fields in which tides propagate. In so far, we decided to keep the title.

**Abstract**

line 7: "polar ozone and water vapor in linking mesospheric tidal variability...": what is "linking" referring to here? maybe you mean "driving", or "contributing to" (but those words would be too strong, see major comment 1). Please rephrase.

Changed: driving

line 8-14: The description of anomalies in tidal amplitudes appears rather clearly written up until line 12, but misses to clarify which wind component the text refers to. Starting in line 11, a distinction is made between zonal and meridional wind components, making me wonder which component was refers to in the earlier sentences? Please clarify.

Changed: a significant negative anomaly in TDT amplitudes in zonal and meridional components is observed.

line 19-22: "The interaction between dynamic processes and the transport of radiatively active gases is important for explaining the observed tidal variability during SSW events": this is not backed up by the results, see major comment.

Removed

**Section 1**

- line 48: are the "modified zonal mean zonal winds" modifying tidal amplitudes via propagation of tidal waves? Please clarify and be more specific on the suggested mechanisms from literature.

Changed

- line 51: "heightened planetary wave activity" - change to "strengthened planetary wave activity"

Changed

- line 54: did the authors meant to distinguish between mixing ratio and ozone density within this sentence?

Deleted: and its vertical structure of the volume mixing ratio (VMR).

- line 61: "ozone dynamics": consider changing to "ozone transport", not sure what "ozone dynamics" are.

Changed

- line 68: I'm not familiar with all the referenced studies, but at least the last three references (Oehrlein et al, de la Camera et al and Hong and Reichler) do NOT analyse tides in the MLT region; they analyze the impact of interactive ozone on stratospheric dynamics including planetary waves. Thus, they cannot serve as appropriate reference for the statements made here.

Added the appropriate reference for the statements made here.

- line 76: QRS and QRL are defined in the abstract, but it would be good to repeat the definition here; also it might be more appropriate to just say radiative heating and cooling here rather than using the variable abbreviations.

Changed

- line 76: it would be good to mention at this point that comparison of water vapour and ozone anomalies from WACCM-X to observations are performed in a first step to ensure consistency with the observational data.

Added sentence: In the first step, we compare water vapor and ozone anomalies from WACCM-X with observations to ensure consistency with the observational data before analyzing their role in tidal variability.

- line 83-84: this description of the structure of the paper is completely generic; it might as well be dropped, or better explain what is done in which section within the previous paragraph.

Dropped

**Section 2**

- line 87: "at three different high latitudes"; consider changing to "at three stations in high latitudes"

Changed

- line 88: continuously in operation in which time period? Please specify.

Specified

- line 90: unclear what is meant by "the same wind retrieval algorithm" - the same over time, between the stations, or the same than in the reference? please clarify.

Clarified

- line 93-94: "tides ... are obtained" - does this mean that the given equation is fitted to the data to obtain the tidal amplitudes? Please be more specific how the equation is used to extract tides.

The adaptive spectral filter is much more complicated than the equation is expressed, although equation (1) is presenting the correct kernel function. The tidal fit is carried out with an adapted window length for each tidal frequency (diurnal tide- 48 hours, semidiurnal tide – 24 hours, terdiurnal tide – 16 hours). We have carried out several tests to optimize the oversampling factor. Furthermore, we included a Gaussian weighting to avoid window effects as they are known for Fourier effects. The solution of the larger windows is used as Tikhonov regularization for the next smaller window for the unfitted tidal components. There is also a constrain about the vertical wavelength of the tide. We mitigate a potential contamination due to the gravity waves by applying a smoothness constrain on the tidal phase (not amplitude). Details are provided by the referenced in the manuscripts. The adaptive spectral filter targets key issues of tidal analysis. The algorithm can handle data gaps and unevenly sampled data, contains full error propagation, and most importantly only requires phase stability with each adapted window length.

- line 98: where are the zonal mean variables obtained from for the analysis of the tides from the meteor radar? Or are they a result of the fitting?

The term zonal mean does not refer to the often used ‘zonal mean zonal’ wind for model analysis. The ‘mean’ refers to the daily average background. Zonal and meridional mean winds represent daily mean values.

- line 100: planetary waves (waves is missing)

Added

- line 106 and line 117: is this the same "QPACK" software, since the reference is the same? If yes, please be consistent in the spelling; if not, clarify.

Yes, changed

- line 132: please provide the approximate altitudes for the MLS data, given that meteor radar observations are provided in altitude coordinates. An interpolation to a consistent vertical coordinate would ease comparisons made later between tidal anomalies and trace gas anomalies.

Changed: Corresponding altitudes are included in the text. Comparisons between tidal anomalies and trace gas anomalies have been interpolated into a consistent altitude:

- line 141: I suggest removing "A comprehensive numerical model.." (both unnecessary and incomplete sentence).

Removed

- line 143-144: "capable of being run ..." consider rephrasing, e.g. simply to "WACCM-X can be run with a coupled or prescribed ...". Generally, I suggest to rather focus on describing the configuration of WACCM-X that is used here, rather than listing possibilities and developments in the CAM/WACCM/WACCM-X framework (this list would be rather long)!

Changed

- line 150-153: I wouldn't agree that the developments described here are "recent" (going back to 2010), nor do I believe they are particularly relevant to be mentioned for the study here.

We agree with that. This sentence has been removed.

- line 155: please rather mention the years of the simulation than saying they are done for the measurement period. Also, are those dedicated simulations performed for this study, or the ones available at: https://doi.org/10.26024/5b58-nc53. If not, what is different?

We have added that the simulation period runs from 2015 to 2023. The simulations used in this study are dedicated runs and differ from the dataset available at https://doi.org/10.26024/5b58-nc53, as the older dataset does not include ozone and water vapor and is only available until 2017.

- line 159: here would be a good place to define the QRL and QRS heating rate variables in detail.

Added: The QRS heating rate is primarily governed by ozone absorption of radiation, while the QRL cooling rate is influenced by the presence of carbon dioxide, water vapor, and ozone.

- General: the information on time period of available observations is largely missing in Section 2. Please add.

Added

**Section 3**

- line 166: please add how many events the composites are based on (so the reader doesn't need to check the compendium for the given period).

Added

- line 174: "altitude of wind reversal": the reversal cannot be seen from the anomalies, consider adding the zero wind contour to the Figures.

Added

- line 181: why would positive meridional wind anomalies be associated with reduced wave activity? Please elaborate.

The polar vortex is reestablished after the SSW as indicated here by the period of intensified westerly winds, the planetary waves are rather weak.

- line 181: please specify in this sentence that the references named here (Dowdy et al and Koushik et al) refer to wind and wave response to SSW in the MLT. As the sentence reads now, it sounds like it refers to the dynamics of the wind reversal in the stratosphere (i.e., the SSW generation itself).

We agree with that. This sentence has been removed.

- line 191: I didn't quite understand how the anomalies in tidal amplitudes are calculates - it says here that they are a "relative change", but the units are m/s; also the phrase "taken as a mean time for the entire showcase period" is not clear to me. Furthermore, it would be very helpful to add a significance test to the anomalies in tidal amplitudes. This way one could infer which anomalies are statistically robust.

The anomaly in tidal amplitudes is calculated as the difference between the tidal amplitude observed during an individual SSW event and the climatological mean tidal amplitude from all years within the same period. The anomaly is obtained by the difference between the climatological undisturbed situations vs all SSW events. We have removed the previous phrasing for clarity. Additionally, we have included the anomalies of tidal amplitude in a case study of SSW events in 2018/2019, which revealed significant anomalies, particularly in DT and SDT. This case study analysis enhances the interpretation of the results and will be added to the revision.

- line 194: percentage difference relative to the mean value (add "relative to")

Added

- line 243: "This indicates...": it is not clear to me what is implied here: that the persistent ozone anomalies are arising from a persistent alteration of the thermal structure (via dynamics), or that the ozone anomalies themselves might give rise, or a least contribute to the persistence of temperature anomalies?

The persistence of positive ozone anomalies reflects prolonged changes in middle atmospheric circulation following the SSW. Additionally, ozone’s radiative effects may contribute to maintaining temperature anomalies, suggesting a potential feedback mechanism.

- line 248: I agree ozone changes are dependent on altitude, but Fig. 6 does not provide information in variations with latitude - for the latitudes shown here, the ozone anomalies are remarkably similar.

We added ozone and water vapor data from a mid-latitude site in Switzerland to confirm the latitudinal differences. Although, the difference between Svalbard and the mainland are small and the general morphology agrees, there is some difference in the ozone VMR.

- line 249: It's not clear to me which altitude, nor process is referred to here: I agree that there might be enhanced tropical upwelling during the SSW event due to pronounced wave driving in the stratosphere; However, enhanced upwelling would reduce tropical ozone in the lower and mid-stratosphere. Please specify which altitudes you refer to here.

We only reference a previous study. Our study does not investigate effects outside the polar vortex.

- line 251: "... a decrease poleward of 40°N. The ozone enhancement ... at mid to high latitudes is consistent...": This confuses me - how is the ozone decrease poleward of 40°N shown by previous work consistent with the enhancement of ozone diagnosed from the observations here? Do you refer to different timings (before versus after SSW)? Please clarify and rephrase.

Reply line 248, line 249, line 251: We have added a figure illustrating the variability of ozone at mid-latitude (Bern, 47°N) in Figure A2a, as measured by ground-based microwave radiometers. This addition helps clarify the differences in ozone behavior at different latitudes and better shows the observed enhancements with previous studies.

- line 253, and general: "ozone increase.. and QRS therein": I agree that changes in ozone should primarily affect the shortwave rather than longwave radiation. Therefore, I am surprised why the authors decided to overlay the QRL contours on the ozone anomalies instead of the QRS fields, which would ease making the link between the tracer changes and the resulting radiative changes.

We have changed the overlaid QRL contours on the ozone anomalies.

- line 253: Here, and at several places I was confused which anomalies are referred to when the "enhancement of STD" is discussed: according to Fig. 3, STD is mainly enhanced just around the SSW event (there is some sign of enhancement later, but very noisy signals including reductions, and I doubt this is significant). However, here the "ozone increase and QRS therein" in the "SSW recovery period (day 20-50)" are suggested to be coincident with the STD anomaly - can you clarify?

The enhancement of the SDT (8 m/s) is most pronounced at the onset of the SSW, particularly when compared to the mean winds (25-30 m/s), resulting in a change of more than 40%. In the revision, we have clarified that the SDT enhancement is primarily associated with the secondary ozone layer in the thermosphere, above 90 km, which aligns with the observed SDT enhancement at these altitudes. This connection addresses the important role of radiative effects of ozone in driving tidal variability during the SSW onset.

- line 257-259: I agree that it is plausible that the ozone anomalies are a main cause of the QRS anomalies, but it would of course be great if this would be quantified, which would be possible e.g. via offline radiation calculations. As is now, the only way to infer the importance of ozone for QRS is the alignment of anomalies, and the rough approximation saying that "mean heating rate by ozone at those latitudes is around 1 K/day". Even more important, the only argument by which the authors rule out the role of water vapour for radiative anomalies is saying that the 25% anomaly "translates to changes in cooling rate of about 0.05 K/day" (line 259). It is not clear to me what this number of 0.05 K/day is based on, and the same holds for the 1 K/day heating by ozone. Given the argument for the importance of the tracers is almost completely based on those numbers, it needs to be made much clearer where they are taken from, for which altitude and latitude region they are valid, and in how far one can linearly scale the radiative impact with the tracer anomalies (as apparently done here).

The ozone data from the stratosphere ozone layer and secondary ozone layer show clear diurnal cycles, which result in a semidiurnal tide at the MLT and a diurnal tide at the stratosphere/lower mesosphere. WACCM-X(SD) fields are in good agreement with the trace gas measurements. We have clarified more details in the added case study of SSW in 2018/2019 and the discussion part. QRS and QRS are not shown in K/day and with a temporal resolution of 3 hours to provide a visual evidence for the difference in their diurnal structure.

- Figs. 6, 7 and 8: great to see the good agreement between the satellite, model and station data! Possibly this result could be emphasized more?

Added: We have added two subsections discussing the water vapor and ozone anomalies, highlighting the comparisons between satellite, model, and station data.

- line 268ff: I agree it is good to calculate the dynamical-driven temperature tendencies in order to compare them to the radative ones. However, for the purpose of the paper and in the following discussion it was not entirely clear to me what this analysis reveals beyond the fact that dynamical heating/cooling is generally balanced by radiative (in particular long-wave) cooling/heating?

We addressed the importance of calculating dynamical-driven temperature tendencies to compare them with radiative tendencies. Our analysis highlights that while dynamical heating/cooling is generally balanced by radiative (particularly long-wave) cooling/heating, the increase in ozone leads to enhanced short-wave heating. However, the direct in situ temperature effect of ozone increase—i.e., stratospheric warming—is intertwined with other factors, such as anomalous vertical descent (negative anomalies in w), which contributes to dynamical heating and influences the total temperature response. It is the feedback mechanism on temperature change. To improve clarity, we have simplified the discussion on dynamical heating/cooling effects and moved the details to the appendixB.

- line 277: ".. the dynamic process drive the persistence of ozone anomalies...": I agree that this is likely the case, but the temperature tendencies do not necessarily help to explain the tracer anomalies - do you suggest it is the anomalous vertical circulation which drives both temperature as well as trace gas anomalies (the later via vertical advection)? Or do you suggest that the temperatures affect ozone via chemistry?

Changed: both dynamic (including eddy effects and vertical advection) and chemical processes drive the persistence of positive ozone anomalies in the upper stratosphere and lower mesosphere. In contrast, water vapor anomalies are primarily governed by dynamical processes, as the mesospheric lifetime of water vapor is on the order of months/years. We have clarified the distinct mechanisms influencing these two trace gases.

- line 281: "still remains in the Earth's shadow..": this would be a good place to provide details on the altitudes which are reached by sunlight as function of latitude. This is addressed by the schematic Fig. 11 later on; if kept, this schematic and the considerations with it should be mentioned here. However, I suggest replacing the schematic Fig. 11 by a figure showing the amount of sunlight in mid-winter as fct of latitude and altitude; this would help to make this point in a more quantitative manner. It could even be shown as a function of daytime to help to make the point on how / where ozone anomalies might affect tidal amplitudes.

We have added a table to show the calculated altitude at these stations.

- line 284: at this point, it appears very speculative to conclude that the redistribution of ozone contributes to tidal variability. I agree this might appear plausible, but the pure quantification of shortwave heating anomalies does not give any quantitative estimate on how strong the effect on tides might be.

We agree with you in pointing out the speculation that the redistribution of ozone contributes to tidal variability. The shortwave heating rate is primarily driven by ozone absorption of ultraviolet radiation. In the revised manuscript, we analyzed the three-hourly anomalies in radiative heating rates (QRL), replacing the hourly anomalies in the manuscript. QRS reveals a clear signature of a diurnal forcing starting 20-30 days after the SSW, which is related to the increased ozone VMR. This result highlights ozone-induced heating anomalies that contribute to tidal variability, providing new insight into the linkage. Furthermore, we want to note that tides in WACCM-X(SD) are mostly driven by the QRS. Below 90 km ozone plays a crucial role for absolute QRS, above other processes become relevant as well. We establish a more clear relationship between both by direct comparisons.

- line 286: results on ozone double layer: I cannot, or barely, see how the double layer of ozone anomalies is reflected in "UV heating" (i.e. QRS) - do I assume correctly that the authors refer to the change of sign in QRS around 10 hPa, visible as change from light blue to light red in Fig. 5 (right)? If yes, it has to be clarified whether the heating in the lower layer is at all different from zero, as this is not apparent from the Figure.

We added new Figures in geometric height showing the altitude of all three ozone layers and their corresponding QRS rates on the same vertical grid. The double layer structure is one of the most clear results in WACCM-X(SD).

- line 286: "these two diurnal tidal waves": do the authors suggest that the double layer of ozone, and thus possibly shortwave heating anomalies, cause two distinct forcing regions of tidal waves? To me, this result appears to be extremely speculative and needs to be justified much better.

Reply: The ozone double-layer structure (stratospheric ozone layer and secondary ozone layer around 90km) is observed in the WACCM-X(SD) ozone anomalies that form at the onset of the SSW and last for about two weeks, resulting in two layers of substantial UV heating. The superposition of these two diurnal tidal waves at the mesosphere may effectively amplify the SDT at high latitudes due to a 12-hour phase offset caused by the different vertical distances both waves have to travel, considering the typical vertical wavelengths of 30-50 km for semidiurnal tides at this latitude (Stober et al., 2021b, 2020).

- line 295: it would be great to give a specific altitude down to which the sun is above the horizon at the given latitudes instead of just mesosphere and stratosphere (see also comment above).

We have added a table to show the calculated altitude at these stations.

**Section 4**

- line 311ff: "explores the enhancement of SDT amplitudes at the onset of SSW ... attributed to zonal wind changes and ozone heating at mid- to low latitudes": This statement added to my confusion on what the authors suggest and present; Firstly, I do not see how the study attributed tidal variability in any way (see main comment); secondly ozone heating at low- to mid-latitudes is not shown in the paper, so this comes somewhat out of nowhere (unless I missed something?). It goes on discussing the STD anomalies during the recovery phase, which I cannot identify from the STD anomalies presented in Fig. 3 (see comment above).

We have added a figure to show the ozone variation at the mid-latitude station Bern (47N). The effect of ozone VMR on the enhancement of SDT at SSW has been clarified in the reply to major comments. Please see.

- line 315ff: also here, I find it hard to follow the arguments by the authors; again a heating rate by ozone is mentioned (0.5K/day), but it is not clear what this value is based on or where it would be valid; further, it is said to be small (with respect to what?), but in the same range than tidal temperature amplitudes (so not small for tidal variability?)

We have added Figures 1 and 14 in the revised manuscript that illustrate the absolute QRS value reaching up to 20 K/day, with a clear diurnal heating cycle in the middle stratosphere. This diurnal forcing cycle is directly related to ozone and can act as a resource for the diurnal tide in the mesosphere. We provide more details in the discussion.

- line 320: again, which time period is referred to for which STD is enhanced by 40%

Reply: SDT shows a positive anomaly of 10 m/s, with changes reaching up to 40% at the onset of SSWs.

- line 322: I agree that radiative effects are more important in the time following the SSW, but for what? For the mean temperature anomalies or the tidal amplitudes? (For the latter, this is not backed up by results).

Reply: Shortwave radiative heating rate is mainly caused by the ozone absorption of UV in the stratosphere, which reveals the diurnal forcing. Additionally, the double-ozone layer (the stratosphere ozone layer and secondary ozone layer) that forms at the onset of the SSW and lasts for about two weeks, results in two layers of substantial UV heating. The superposition of these two diurnal tidal waves at the mesosphere may effectively amplify the SDT at high latitudes due to a 12-hour phase offset caused by the different vertical distances both waves have to travel, considering the typical vertical wavelengths of 30-50 km for semidiurnal tides at this latitude. This cooling of the middle atmosphere defines the large-scale temperature field and the stratification of the middle atmosphere between the polar and middle latitudes drives the circulation and provides the background condition for the propagation of planetary, tidal, and gravity waves.

- line 325ff: the discussion of the DT is much better to follow and to comprehend compared to the discussion on STD.

Reply: The ozone data from the primary and secondary ozone layer shows clear diurnal cycles, which result in a SDT at the MLT and a diurnal tide at the stratosphere/lower mesosphere. Please see the discussion in the revised manuscript.

**Section 5**

- line 355: I disagree that a deeper understanding on mechanism is provided (see main comment 1)

Changed: This study provides a comprehensive quantification of tidal variability and co-located tracer variability by combining observational data with model simulations and discusses the radiative effects of tracer anomalies on mesospheric tidal variability during SSWs.

- line 361-362: the altered background presumably affects propagation, but this not quantified here. Please clarify that this is a proposed mechanism, rather than a result of the study.

Clarified