Response to referee#1's comments for the manuscript

General Comment:

I apologize if my initial requests for major revisions were too much to be reasonably incorporated within the time frame given to the authors.

General reply:

We thank the reviewer for the honest words. We take this statement as motivation to learn and deepen our understanding.

Comment:

My original concern with the article was that it did not sufficiently quantify the contributions of the different drivers of tidal variability, including that of radiative effects, even though this is central to the paper's theme. I would argue that this concern largely stands also in the revised manuscript. For example, the authors write in the conclusion that "The observed SDT amplification is primarily attributed to the ozone VMR dynamical effect and modified by radiative heating effects modulated by ozone variability", while also arguing that the results of this work provide insights in the coupling between trace gas variations, radiative heating, and tidal variability. Without dedicated analysis quantifying the exact radiative tidal forcing perturbation terms, as well as the actual tidal wind perturbation that would result from these perturbations, this coupling is not identified but is only alluded to. In my view, the presented evidence is not strong enough to provide credibility to the proposed mechanism.

Reply: The raised concerns are mitigated by adding a detailed description on how WACCM-X QRS and QRL fluxes are calculated. We also added in the discussion that ozone and water vapor are considered proxies for its heating and cooling rates. The exothermic heating at the MLT due to atomic oxygen is still modulated by the diurnal variation of ozone. We add this in more detail to the revised manuscript.

Replies to a select few of the author's replies to reviewer comments are given below.

Comment:

Author Reply: The SSW events are already presented in a table in our paper, which we have cited accordingly. In this study, we focus specifically on major SSWs that occur in mid-winter (January and February) and do not consider events with onsets such as March 24th, 2010. Generally, SSWs occurring in early spring are referred to as final stratospheric warming (FSW) events rather than major SSWs. Additionally, we confirm that the reference model from the cited NOAA page is MERRA-2. Following the list of events that the paper refers to, the 24th of March 2010 is classified as a major SSW. A major SSW in March does not necessarily imply that it was a final warming, even if in this case this may have been so. Indeed the list of major SSW dates includes the definition that the events are only counted if they occur before the 10th of April. I further fail to see why this being a final warming would fundamentally change the relevance of the proposed mechanism. On the contrary, due to the much higher abundance of short-wave radiation in March, I would expect the March event to be a prime example of the proposed mechanism.

Reply: There is indeed a significant difference between very late SSWs and those in January and February. Tertiary and secondary ozone are quiet different in March and April. However, the proposed effect requires multi-layer heating to get some kind of mixing effect. Climatologies of the tertiary ozone VMR show that this layer disappears in March.

Comment:

It was not clear that the modeled SSW analysis is based on only 4 simulated SSW events spread over 9 years of simulation data. With this low number of event events and simulation years, statistical significance should be discussed. Basically half the data set now contains a major SSW in January/February. Surely this must cause contamination of the climatological model average from which the anomalies are calculated? Especially when looking at such long periods before and after the central SSW dates (spanning 130 days in total). SD-WACCMX v2.1 data is freely available for download spanning many decades of simulations, including the short-wave and long-wave radiative heating fields.

Reply: A key aspect of this study are the radiometric observations at Ny-Alesund. The WACCM-X data was added to guide the interpretation of the observations and to compare our measurements with the model. Furthermore, we had to perform our own runs, as all other available WACCM and WACCM-X runs, we are aware of, did not contain QRS, QRL, ozone and water vapor with a sufficient temporal resolution to investigate the effects of SSWs. We also analyzed the Specified Dynamics (SD/WACCM-X) simulation run from Gasperini et al., 2020 and an even longer one back to 1980. However, the required fields were only available as monthly mean profiles and, thus, not suitable for this type of study.

Comment:

Author Reply: 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). From what I can see, the cited works of Stober et al. (2021b, 2020) provide detailed analysis of seasonal semidiurnal tidal characteristics, as well as its response to SSWs. This includes a description of the tides' vertical wavelength. However, as stated in my original review, I still can't see how the sum of two superposed 24 hr waves can (effectively) amplify the STD. The sum of two 24 hr waves is always a 24 hr wave itself. Even if one would imagine two diurnal waves with a 12 hr phase offset overlain only with the STD, the wavelength of the STD covers only half a wavelength of the DT. In time-frequency (Fourier) analysis, the 12 hr and 24 hr wave forms are also orthogonal. If it is implied that a 24 hr waveform (the sum of two 24 hr waves) affects the solution to the 12 hr waveform's amplitude, this sounds like a short-coming of the analysis.

Reply: The superposition of two oscillations with the same periods results in a new oscillation of that period. However, waves are vectors and the superposition of two waves can lead to wave mixing. The mixing of waves is given by its product of the amplitude, and the child wave can reach substantially larger amplitudes as both source waves.

Comment:

Author Reply: 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.

The visual evidence does not look convincing, as the amplitude of the 24 hr wave forcing (or 12 hr and 8 hr wave forcing) cannot be estimated by eye. The peak daily heating rates might correspond to only a very short period of insolation, therefore not necessarily resulting in a prominent 24 hr wave forcing. As for the first review, I suggest time-frequency (Fourier) analysis of the 3-hourly modeled heating rates to determine the actual amplitudes of the diurnal, semidiurnal and terdiurnal wave forcings.

Reply: We explicitly wrote in the discussion that the true heating is likely not 24 hours. However, to furthermore substantiate the excitation of tidal waves in the wind we added a Figure showing the results of the adaptive spectral filter for diurnal and semidiurnal wind perturbations for two selected periods during the SSW 2018/19 above Tromso.

Final comment:

Line 151 of the revised manuscript references Liu et al. (2010a) for a description of the radiative transfer scheme used in WACCM-X. I think it is important to mention all relevant (E)UV absorbing trace gases by name also in your paper, since it is the focal point of your work. Liu et al. (2010) Figure 2 further shows that atomic oxygen number densities surpass that of ozone above approximately 65 km altitude. Since atomic oxygen absorbs UV radiation and is important to the energy budget of the upper atmosphere, its importance/relevance to the short-wave radiation perturbations should be discussed. Especially because QRS shows a maximum above 80 km concurrent with reduced ozone variations in Tromsø in Figure 2 of the revised manuscript.

Reply:

We added explicitly the importance of atomic oxygen and exothermic heating in the MLT region in the revised manuscript. Atomic oxygen is still closely related to the diurnal cycle of ozone and, thus, the total heating from ozone, water vapor and atomic oxygen still would reflect a diurnal pattern. We explicitly wrote in the discussion that ozone and water vapor are only proxies for the heating and cooling rates and other species contribute as well.

Response to referee#2's comments for the manuscript

The revision of the manuscript by Shi et al. addressed most comments and concerns, and the revised manuscript is overall improved. It is stated more clearly that the causality between tracer anomalies and tides is not yet proved by the analysis, the inconsistencies in the description of the STD tide anomalies have been clarified (even though I still find the proposed mechanism very speculative, see below), as well as the methodological description. However, there are still some parts that I find hard to follow (e.g., in the discussion). I appreciate the work going into the addition of the case study, but have to admit I do not see how this helps to clarify the raised concerns, or how it adds value to the paper. Overall, I recommend minor revisions, with specific comments as detailed in the following.

Main comments:

- General comment on Section 3.1., case study, and on connection of QRS and ozone: While I appreciate the addition of the case study, I have to admit that I do not quite see the additional value. In the response, one of the reasons given for adding the case study is that it reveals the diurnal cycle in the QRS forcing more clearly - however, this is also apparent in the added Figure 14 of the composite analysis. Indeed, in the case study the connection of the ozone variations and QRS is less clear to me - ozone shows a clear diurnal cycle also at high altitudes (80 to 100 km), while QRS does not. If ozone is the primary forcer for QRS, this seems inconsistent.

Another reason for adding the case study is given in response to my comment on adding significance tests to the tidal anomalies (previous comment on line 191); the authors reply that the case study reveals significant anomalies, but I do not see that a significance test has been performed here. If anything, the tidal anomalies of the case studies appear much more noisy compared to the composite, so I would rather think the opposite is true (the case study is less significant). I still would recommend the authors to perform a significance test (probably a simple T-test is sufficient, testing whether the anomalies are different from zero) on the anomalies of the composites, which would add value to the study. One reason I could see for adding the case study is the detailed comparison of WACCM-X results and MR+MERRA - if so, I recommend to state this more clearly and to focus on this part.

Reply: The primary motivation for including the case study is to provide a detailed comparison between WACCM-X/SD and observational datasets from MR and reanalysis data MERRA-2 during an individual SSW event. Meteor radar measurements more accurately capture mesospheric winds and tidal amplitudes. WACCM-X/SD complements these observations by offering a more comprehensive representation of the vertical structure of the stratospheric and secondary ozone layers, particularly the clear diurnal cycle of shortwave radiative heating (QRS) in the stratosphere during SSW, which is essential for understanding the proposed forcing mechanisms. The case study helps interpret the subsequent composite analysis of tidal and trace gas anomalies. The revised manuscript now clearly distinguishes the stratospheric ozone layer and the secondary ozone layer (around 90 km). In the stratosphere, QRS is dominated by short-wave ozone heating, leading diurnal cycle. In the MLT regions, we added explicitly the importance of atomic oxygen and exothermic heating at high altitudes (80 to 100 km) in the revised manuscript. Atomic oxygen is still closely related to the diurnal cycle of ozone and, thus, the total heating from ozone, water vapor and atomic oxygen still would reflect a diurnal pattern. A new schematic (Fig. 18) illustrates how mixing of two diurnal heating waves can propagate and amplify the enhanced semidiurnal variability via wave-mixing.

- Mechanism of STD enhancement: I can follow now the reasoning by the authors, in that they propose that the strong STD enhancement just after the SSW onset is connected to a superposition of DT generated by shortwave forcing (in turn driven by ozone anomalies) in the stratosphere and MLT, and that a phase shift in the upward propagation of the stratospherically DT leads to the STD anomaly higher up. This is an interesting mechanism, but if the authors want to go beyond speculating on this mechanism, additional analysis would be necessary. For example, the 12h phase shift is argued based on typical wavelength, and on Fig. 1 (see line 440). I agree there is some phase shift apparent in Fig. 1, but it is nearly impossible to clearly identify the amount of phase shift by eye in this Figure. This argument could be strengthened by explicitly analyzing the phase shift. Furthermore, if this superosition was the case, wouldn't one expect an anomaly in the DT in the stratosphere around the same time than the STD anomaly? However, the DT only sets in after day ~20 (Fig. 8), which is consistent with the strengthening QRS anomalies in the stratosphere around this time. As detailed in the following, I recommend the authors to clearly state what is shown in the paper, and which connections or mechanisms are rather speculative.

Reply: We appreciate the reviewer’s thoughtful assessment of our proposed mechanism regarding the enhancement of the semidiurnal tide following the SSW onset. We hypothesize that this enhancement may result from the mixing of diurnal tidal waves generated by QRS, mainly resulting from ozone in the stratosphere and ozone, atomic oxygen, and other chemical species in the mesosphere/lower thermosphere. The mixing of both diurnal tides could potentially lead to wave mixing between both diurnal tides that amplify the semidiurnal amplitude. In the revised manuscript, we will clarify the phase shift. Depending on the vertical wavelength of the stratospheric diurnal tide, there is a certain phase offset of the arrival time between the MLT radiatively forced diurnal tide and the one propagating from below. We added a Figure showing the results of the adaptive spectral filter for diurnal and semidiurnal wind perturbations for two selected periods during the SSW 2018/19 above Tromsø. Regarding the timing of the DT and STD anomalies, we will address this apparent discrepancy more explicitly and propose that the spacing between the layers of absorption, as well as the effective vertical wavelength of the diurnal tide play a crucial role in the SW2 enhancement.

We performed a spectral filtering of the QRS to extract the DW1 and SW2 modulation and overlayed the filtered QRS over the winds and temperatures from WACCM-X(SD). We added temperature to illustrate that these tides propagate upward and that the magnitude of the excitation from the QRS is approximately reasonable for the temperature tidal amplitude. The semidiurnal modulation of the QRS at the mesosphere (80-90km) shows a clear enhancement of the semidiurnal modulation at the time of the enhancement around the SSW. We just present it as a diagnostic. We won’t claim that the QRS is the sole driver, but apparently, the QRS semidiurnal modulation leads the enhancement.

Minor comments:

- line 189: can you specify how the MR + MERRA product was merged? Is it simply MERRA below a certain altitude, and MR above, or is there a transition?

Reply: The MR + MERRA product uses MERRA-2 data below a certain altitude (white horizontal line), and meteor radar (MR) observations above. There is no transition.

- line 193: can you specify what is mean by "overlapping region" here?

Changed: Zonal winds agree within 2–5 m/s in the altitude region around 75 km, where both MERRA-2 and MR provide valid data and their coverage largely overlaps.

- line 212: given the QRL is tightly coupled to temperature, showing temperature anomalies could be helpful (same applies to composite Figures)

Added the figures in the appendix.

- line 214: Is the statement, that QRL seems to be partly driven by water vapour changes based on the spatial coherence? Given that in the next sentence, it is argued that it is unlikely that water vapour is the main driver, please consider re-formulating to something like: "These changes in the cooling are aligned with water vapour anomalies, but given the mean cooling rate..."
Changed

- line 218: "For the short-term...": this is what will be argued in the paper in the following, rather than a fact, is it? I recommend removing the sentence, or changing it to "might play a role"; Or if this is meant as a fact, add a reference that proofs this connection.

Changed

- line 220: are the anomalies of the secondary ozone layer really caused by transport ("intrusion and exchange of air masses"), or rather by changes in the local chemistry, e.g. due to temperature? Given the diurnal cycle in ozone, i.e., short lifetime, the latter appears more plausible to me.

Changed: Furthermore, the primary driver of disturbances in the secondary ozone layer is more likely related to temperature-dependent chemical processes. Atomic oxygen is still closely related to the diurnal cycle of ozone and, thus, the total heating from ozone, water vapor and atomic oxygen still would reflect a diurnal pattern.

- line 241: I personally prefer the term "composite" over "superposed epoch", but this might be a matter of taste and/or differences in disciplines which term is more common (in stratosphere/troposphere analysis of SSWs, the term "composite" is commonly used).

Changed

- line 328: remove "reduced" before water vapour, as there are both positive as well as negative anomalies.

Changed
- caption Fig. 12: should read ozone, not water vapour.

Changed

- line 371ff: discussion on impact on tides: I recommend moving this to the next section, where the heating rates are discussed and shown.

Changed

- line 376ff (starting with "With the polar wind ..."): following up a previous comment, I still do not see why those sentences on ozone at low and mid-latitudes are added here - is this meant to point out that other studies have found signals at other latitudes (if so, re-write to make this clear), or as comparison to results shown here? If the latter, it might be good to move those sentences to Section 4, where the additional analysis from a mid-latitude station is shown. Another potion would be to simply remove the sentences.

Removed

- line 392: The QRS heating might not be exclusively driven by ozone (see e.g. line 517), so please remove the bracket, or add "(including effects by ozone)".

Changed

- line 394: "reduced heating": The anomalies are still positive, but not as strong, correct? Please rephrase.

Changed

- line 395: "captures the diurnal cycle": I can only see the diurnal cycle at lower altitudes in the stratosphere, but not in the MLT, where primary anomalies are found. Please clarify.

Clarified: Furthermore, the QRS shows a good correspondence to the ozone VMR and captures the diurnal cycle in the stratosphere.

- line 401 / Fig. 14: Overlaying contours of temperature (anomalies) might be helpful in the discussion of the strong connection of longwave cooling and temperatures.

Changed

- line 420: please clarify at which altitudes the QRS anomalies occur during which times - in the MLT around the SSW onset, and in the stratosphere 20-60 days later, correct?

Clarified: The largest QRS values are observed after the central day of the SSW at the MLT, and subsequently in the stratosphere about 20 to 60 days later, when the elevated stratopause reaches again the typical stratospheric altitudes.

- line 449: please refer the reader to the appendix for the tide anomalies in WACCM-X.

Changed

- line 457: Here would be a good place to state that the delay in the QRS (and thus DT) response in the stratosphere is related to the increasing sunlight over the season. This makes for a good transition to the following paragraph on the illumination heights.

Added: The delayed response of QRS (and consequently DT) in the stratosphere is likely associated with the seasonal increase in solar illumination, as sunlight progressively reaches lower altitudes.

- line 501: I recommend removing this part on longwave heating (starting with "However,.."), as it adds no new insights revealed by the study.

Reply: Longwave cooling rates play the crucial role of the background condition for the propagation of tidal waves by analyzing the dynamical effect term, as well as shortwave heating rates.

- line 510: not sure what " a proxy of the changes" refers to - please clarify.

Changed: a proxy of the radiative heating changes

- line 517: this is an important information, that was mostly omitted in the discussion of the results so far. Please check the previous sections to state more clearly that in the MLT, not only ozone is influencing shortwave heating rates.

Reply: We added explicitly the importance of atomic oxygen and exothermic heating in the MLT region in the revised manuscript. Atomic oxygen is still closely related to the diurnal cycle of ozone and, thus, the total heating from ozone, water vapor and atomic oxygen still would reflect a diurnal pattern. We explicitly wrote in the discussion that ozone and water vapor are only proxies for the heating and cooling rates and other species contribute as well.

- line 519: as discussed previously, longwave radiation is mostly a function of temperature, and the effects of water vapour cannot easily extracted (and might be small above the lower stratosphere). Thus, I recommend to remove the sentences starting with "The longwave cooling...", as it adds no new information.

Removed

- line 538ff: I appreciate the effort of adding the additional stations at mid-latitudes. However, I have to admit it is not clear to me what this analysis adds for the conclusions of the paper. Please clarify.

Reply: The mid-latitude observations are used to map the latitude–dependent SSW signatures and to identify the transition zone where dynamical and chemical effects of SSWs fade. Collm (51.3° N) still lies near the polar-vortex edge and therefore retains weakened—but detectable—tidal anomalies, whereas Zimmerwald/Bern (47° N) shows no obvious ozone and water vapor response to SSWs. The contrast demonstrates that (i) the high-latitude stratospheric ozone increase and the short-wave radiative heating (QRS) that are associated with the enhancement of the diurnal tide (DT) after SSW onset (20-50 days) and (ii) Applying the same epoch analysis to the ozone and water vapor measurements from GROMOS and MIAWARA at midlatitudes reveal no discernible signatures associated with the SSW events. Therefore, the positive ozone anomalies in the stratosphere and MLT at high latitudes act as radiative drivers that accompany upward-propagating diurnal waves, forcing stronger SDT amplitudes in the MLT at the onset of SSW.

- line 584: Please consider re-phrasing to "... driven by stratospheric ozone anomalies, whose radiative impacts become effective 20 -30 days after the SSW onset due to the strengthening solar radiation over the season."

Changed

- line 587: no attribution to dynamical effects was presented here, so consider re-phrasing to "... is likely primarily due to dynamical effects, ..."

Changed

- line 590: see comment above, please clarify here that this is the proposed mechanism that needs to be shown in future studies.

Added