Response to referee#3's comments for manuscript

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).

Major comments:

1. The latitude ranges used are confusing. According to the text, the zonal wind in Figure 1 is at 60N but the omega* anomalies and temperatures are 70-90N. Wouldn't it therefore be more sensible to show the zonal wind at 70N. Can the authors can provide a reason why they did not do this?

   We use the zonal wind at 60°N based on the definition of the major SSW and early FSW: zonal-mean zonal wind at 10 hPa and 60°N (Christiansen 2001; Butler 2015; Baldwin 2021). By displaying the zonal wind data at 60°N, the aim is to capture the broader-scale circulation features, including the subtropical and mid-latitude regions, which can significantly influence the dynamics of the polar vortex and planetary wave propagation. In our study, we focused on the polar regions, therefore, we show the temperature and omega* anomalies inside the polar cap between 70-90°N.

   (a) Christiansen, B., 2001: Downward propagation of zonal mean zonal wind anomalies from the stratosphere to the troposphere: Model and reanalysis. J. Geophys. Res., 106, 27307–27322, doi:10.1029/2000JD000214.

   (b) Butler, A. H., Seidel, D. J., Hardiman, S. C., Butchart, N., Birner, T., and Match, A.: Defining Sudden Stratospheric Warmings, Bulletin of the American Meteorological Society, 96, 1913 – 1928, https://doi.org/https://doi.org/10.1175/BAMS-D-13-00173.1, 2015

   (c) Baldwin, M. P., Ayarzagüena, B., Birner, T., Butchart, N., Butler, A. H., Charlton-Perez, A. J., Domeisen, D. I., Garfinkel, C. I., Garny, H., Gerber, E. P., et al.: Sudden stratospheric warmings, Reviews of Geophysics, 59, e2020RG000 708, 2021.

   (d) Butler, A. H. and Domeisen, D. I.: The wave geometry of final stratospheric warming events, Weather and Climate Dynamics, 2, 453–474, 2021.

2. Ideally I would have thought that his study would be done using some type of coordinate relative to the vortex edge, but perhaps this is difficult in the mesosphere. However, given that the authors have chosen 70N, it would be useful to have some indication of what fraction of the 70-90N area is inside-the-vortex (at least at levels where the vortex can be defined) at the time of the FSW and SSW events. Perhaps the answer is "almost all of it". If this is the case please state this.

   In our study, we mainly focused on the ozone anomalies over the polar regions 70-90 °N after SSW and FSW events. Especially, for SSW, the polar vortex is split or displaced by the planetary waves as shown in Fig. 1 for 2018, 2019, and 2021 SSW events. As suggested by the reviewer most of the volume is inside the polar vortex until the SSW or the FSW events. During these events, it is no longer feasible to define a polar vortex until it recovers.

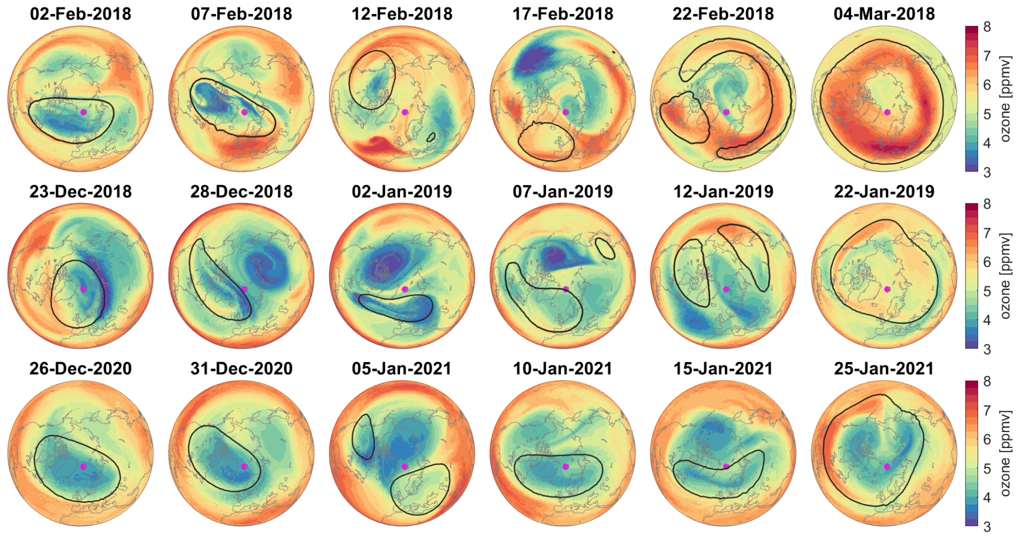

FIG. 1. Ozone volume mixing ratio variability at 10 hPa from ERA5. The edge of the polar vortex and the location of the Ny-Alesund, Svalbard.

Minor comments:

1. Line 194 – "The main benefit of the ground-based observations is the much higher temporal resolution of two hours, which permits to estimate of the sampling bias from the satellite MLS taking data only at two local times." There is no discussion anywhere else in the study suggesting that MLS sampling bias is a problem for this study, so please either delete this sentence or explain why it is relevant.

   Ozone shows a distinct diurnal cycle with up to 60% change depending on local time at the middle/upper stratosphere and lower mesosphere (Schranz et al., 2018), which varies with season. MLS samples at fixed local time and, thus, will always measure ozone at a certain time within this diurnal cycle. That's why we compare GROMOS-C and zonal mean MLS ozone observations.

   Schranz, F., Fernandez, S., Kämpfer, N., and Palm, M.: Diurnal variation in middle-atmospheric ozone observed by ground-based microwave radiometry at Ny-Ålesund over 1 year, Atmos. Chem. Phys., 18, 4113–4130, https://doi.org/10.5194/acp-18-4113-2018, 2018.

2. Line 198 says "The results indicate a good agreement between MERRA-2 and MLS with GROMOS-C observations.", yet in figure 3 – MERRA-2 ozone at altitudes above 0.1 hPa is clearly not in agreement with MLS and GROMOS data.

   Changed: The results indicate a good agreement between MERRA-2 (below 0.1 hPa) and MLS with GROMOS-C observations. However, due to the complexity of altered dynamics in the winter polar regions introducing additional uncertainties into numerical models and data assimilation systems (Wargan et al., 2017), ozone VMRs exhibit dramatic variability (in Fig. 3b, e) in the mesosphere from MERRA-2.

   Wargan, K., Labow, G., Frith, S., Pawson, S., Livesey, N., and Partyka, G.: Evaluation of the ozone fields in NASA's MERRA-2 reanalysis, Journal of Climate, 30, 2961–2988, https://doi.org/10.1175/JCLI-D-16-0699.1, 2017.

3. Figure 4 – Given the MERRA-2 ozone values shown in Figure 3, it does not seem sensible to show these ozone anomalies from 0.1 to 0.01 hPa in Figure 4.

MERRA2 ozone values are provided up to the altitude level of 0.01 hPa. It is true that the ozone volume mixing ratio in MERRA2 seems unrealistic. We explicitly point that in the revision of the MERRA2 plots and remove these altitudes between 0.1 and 0.01 hPa in the anomaly Figures. Due to the complexity of altered dynamics in the winter polar regions introducing extra uncertainties into numerical models and data assimilation systems (Wargan et al., 2017), ozone VMRs exhibit dramatic variability (in Fig. 3b, e) in the mesosphere from MERRA-2.

4. Line 360 - The authors claim an increased occurrence of SSW events during midwinter in the NH. This is not shown or referenced anywhere else in the paper. The statement regarding early FSW events is similarly problematic.

   Between 2003 and 2022 about 10 major SSW events occurred in the northern hemisphere, whereas only 1 event was reported in September 2019 Antarctic SSW in the southern hemisphere within the same period. The total number of events also depends on the methodology to classify SSW events (see reply above). The FSW events were compared to the classification presented by Matthias et al., 2021.

   Matthias, V., Stober, G., Kozlovsky, A., Lester, M., Belova, E., Kero, J. (2021). Vertical structure of the Arctic spring transition in the middle atmosphere. Journal of Geophysical Research: Atmospheres, 126, e2020JD034353. https://doi.org/10.1029/2020JD034353

5. Line 395 – It is not clear what point this sentence is trying to make. The claim that "ozone chemistry has become increasingly important in governing climate variability" certainly needs some justification that is not to be found here.

   There have been several studies showing that the polar vortex dynamics are key to understanding polar ozone VMR (Sun et al., 2014; Banerjee et al., 2020; Schranz et al., 2020, Shi et al., 2023). Due to the ban of chlorofluorocarbons (CFCs) in the Montreal protocol ozone depletion was supposed to stop, and a trend reversal in the circulation is expected. Recent studies show such a trend reversal; however, it is not yet confirmed whether the ozone recovery or the increased carbon dioxide is causal for the changes in dynamics. Monitoring ozone in the stratosphere and lower mesosphere remains therefore a high priority and is supported by the Global Atmospheric Watch Programm (GAW). We will add the references and some explanations.