Response to Reviewer – 'Ozone and water vapor variability in the polar middle atmosphere observed with ground-based microwave radiometers' by Guochun Shi et al.

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

In this paper, time-series of stratospheric and mesospheric ozone and water vapor profiles observed from the high-latitude station Ny Alesund with the two ground-based Microwave (MW) radiometers MIAWARA-C and GROMOS-C are discussed. Time-series and climatologies are compared against MLS/AURA satellite observations and MERRA-2 reanalysis data, and the annual and interannual variability is discussed for Ny Alesund based on all three data-sets, and for a "conjugate station" at high SH latitudes based on MLS and MERRA-2 data. Ascending and descending rates in summer respectively winter are derived for the NH from the ground-based MW observations and MLS, for the SH for MLS only. MLS and the ground-based instruments agree very well, both regarding the absolute values up to the mid-mesosphere and the day-to-day variability, while MERRA-2 shows systematic differences to both the ground-based MW observations and MLS in the mesosphere, and to MLS in the SH lower stratospheric ozone hole area. However, considering the low vertical resolution of the ground-based MW observations, it might be more appropriate to degrade MLS and MERRA-2 data to the vertical resolution of MIAWARA-C respectively GROMOS-C before computing the relative differences. However, the good agreement with MLS data demonstrates a high quality of the MIAWARA-C and GROMOS-C instruments, and ground-based observations like these will be of increasing importance in the near future when the last remaining satellite limb observing instruments have reached the end of their lifetime, to continue long-term time-series at least locally, to constraint models like MERRA-2, and hopefully to provide a connection to future limb satellite missions, though the only limb sounder mission that I know of with a coverage comparable to MLS is the Earth Explorer 11 candidate mission CAIRT, with EE11 expected to launch in the early 2030s. In this sense, the presentation of the MIAWARA-C and GROMOS-C data, their evaluation against MLS, and discussion of properties derivable from these data, are very valid and important results adequate for publication in ACP (or AMT).

However, in its current stage, it was not clear to me what the main focus of the paper is – evaluation of the data, derivation of stratospheric annual and interannual variability, interhemispheric differences? – as all these aspects are somewhat mixed together. In my opinion, the paper could become much more clear and concise by restructuring it in such a way that the different aspects are clearly separated. As the evaluation of the MIAWARA-C and GROMOS-C data is an important prerequisite for using them to derive annual/interannual and interhemispheric variabilities, this should be discussed first. Results concerning the interhemispheric differences in the dynamical variability of the stratosphere mainly confirm previous results; what is new here is the instruments used, as well as the concise derivation of descent and ascent rates in both hemispheres from the climatological annual variation of H_2O. This is an interesting comparison, though I don't really follow the argument that this is evidence for interhemispheric coupling; this point needs a more detailed explanation.

We appreciate your insightful comments regarding the clarity and organization of the manuscript. We agree that the current manuscript can be improved to highlight the main focus better and separate the different aspects of our study. We understand that the current combination of data evaluation, derivation of stratospheric annual and interannual variability, and interhemispheric differences may have resulted in a lack of clarity. In the revised manuscript, we will discuss the data evaluation process prominently in the initial sections of the paper, then, clearly explain annual and interannual variability and a more detailed explanation of the comparison of descent and ascent rates derived from the climatological annual variation of water vapor. We will give a more detailed explanation of the evidence for interhemispheric coupling and expand upon this aspect in the revised manuscript, providing a more comprehensive explanation of the relationship and its implications.

A few minor issues are listed below.

Abstract: state altitude / pressure range of investigation, as well as time-period (2015-2021?) and the vertical range and times of year over which the descent/ascent ranges have been determined.

Changed the sentence as follows:

In the northern hemisphere, the water vapor ascent rate (05 May to 20 Jun from 2015 to 2018, and 15 Apr to 31 May from 2019 to 2021) is 3.4±1.9 mm s−1 from MIAWARA-C and 4.6±1.8 mm s−1 from Aura-MLS, and descent rate(15 Sep-31 Oct from 2015-2021) is 5.0±1.1 mm s−1 from MIAWARA-C and 5.4±1.5 mm s−1 from Aura-MLS at the altitude range of about 50-70 km. The water vapor ascent (15 Oct to 30 Nov from 2015-2021) and descent rates (15 Mar to 30 Apr from 2015-2021) in the southern hemisphere are 5.2±0.8 mm s−1 and 2.6±1.4 mm s−1 from Aura-MLS, respectively.

Line 37: The meridional transport of trace gases into the polar cap is controlled by the strength of the polar vortex …. Add: during polar winter.

Changed the sentence as follows:

The meridional transport of trace gases into the polar cap is controlled by the strength of the polar vortex during polar winter, which is driven by the temperature gradient between the polar cap and the mid-latitudes through the thermal wind balance in the hemispheric winter stratosphere, and forms an essential barrier separating ozone rich air at the mid-latitudes from ozone depleted air within the polar cap.

Sentences in lines 69-70 and 70-71 have partly redundant information, and could be shortened accordingly.

Changed the sentence as follows:

It can be specially designed for measuring ozone and water vapor which is valuable as it complements satellite measurements, is relatively easy to maintain and has a long lifetime, and is operated from different locations on a campaign basis (Scheiben et al., 2013, 2014).

Line 74-76: please clarify in this sentence that MLS data are used to provide the observations for the conjugate station.

Changed the sentence as follows:

Here, we present a detailed comparison of ozone and water vapor observed by Aura-MLS at conjugate latitude station leveraging multiyear ground-based observations from GROMOS-C and MIAWARA-C performed at Ny-Ålesund and Aura-MLS data as well as reanalysis data.

Sections 2.1, 2.2, 2.3: Instrument descriptions: please add from when to when data are available, as well as the instruments precision/noise error, to the descriptions of GROMOS-C, MIAWARA-C, and MLS

Changed the sentence as follows:

In this study, we use ozone and water vapor measurements from our two ground-based microwave radiometers GROMOS-C and MIAWARA-C which are only available to measure at single locations and, thus, are representative of a specific geographic location. Both instruments are located at Ny-Ålesund, Svalbard (79◦ N, 12◦ E) and collected continuous data since September 2015. We extract the interannual ozone and water vapor variability between Jan 2015 and Dec 2021 from MERRA-2 and Aura-MLS over the northern polar station, between Jul 2015 and Jul 2022 from MERRA-2 and Aura-MLS over the southern polar station. The corresponding virtual conjugate latitude station (79◦ S, 12◦ E) is shown in Fig. 1. Additionally, we use temperature observations from Aura-MLS.

GROMOS-C and MIAWARA-C precision/noise error: please see the reply to the first major comment of reviewer1.

MLS precision/noise error:

The estimated temperature single-profile precisions are 1 K at 100 hPa, 0.5 K at 10 hPa, 0.8 K at 1 hPa, 1 K at 0.1 hPa, 1.2 K at 0.01 hPa, and 2 K at 0.001 hPa.

The estimated ozone single-profile precision reported by MLS Level 2 v1.5 software varies from 0.2 to 0.4 ppmv from the mid-stratosphere to the lower mesosphere.

The estimated water vapor single-profile precision reported by MLS Level 2 v1.5 software is 0.2–0.3 ppmv in most of the stratosphere and increases to 0.7-0.8 ppmv in the middle mesosphere.

Section 2.4, MERRA-2 description: please add description how ozone and water vapor information is derived within MERRA-2. Data assimilation (which altitudes), photochemical model (how detailed)? This information is important to understand the deficiencies of MERRA-2 compared to the observations shown in later sections, and should already be provided here.

We agree and as suggested by the reviewer, therefore, we added the description how ozone and water vapor information within MERRA-2 in Section 2.4.

Line 154: Fig. 2 shows that the ozone VMR starts to increase …

Changed the sentence as follows:

Fig.2 shows that the ozone VMR starts to increase up to the maximum value of about 8 ppmv for some of the years in the stratosphere when the polar vortex is disturbed or weakened by the planetary waves leading to the formation of sudden stratospheric warming events.

Lines 163-164: this sentence appears to end in the middle

Changed this sentence appears to end in the middle.

Lines 164-165, 169-170: I think these details about ozone in the MERRA-2 dataset should be presented in the description of MERRA-2 in Section 2.3 already. That would make the argument here more simple – it seems to be a known and well-understood bias in MERRA (at least it is consistent with what I would expect from a model that uses a simplified stratospheric chemistry scheme in the mesosphere).

These sentences have been modified in Section 2.3.

172-173: below 1 hPa. If you look closely, you will note that the annual variation in MERRA-2 ozone is significantly different from the observed variation throughout the mesosphere above 1 hPa.

Changed this sentence as follows:

Remarkably, Fig.2 shows the consistencies of GROMOS-C with both MERRA-2 and Aura-MLS datasets in time series of ozone below 1 hPa. A clear annual cycle in the stratosphere is well captured by all datasets, and the higher variability of ozone in winter and spring seasons is clearly visible.

Line 189-190: erase either the captured, or the agrees

Changed the sentence as follows:

In general, MIAWARA-C the annually varying mesospheric distribution of water vapor agrees well with reanalysis data and satellite observations.

Line 202-213, discussion of ozone and water vapor at conjugate latitudes: the differences in the stratospheric dynamics between NH and SH and its impact on stratospheric ozone is fairly well known, and well understood. I see two take-away messages from figures 4 and 5: (1) while MERRA-2 generally does a good job in reproducing the variability of stratospheric ozone and water vapor, it fails in the mesosphere as discussed in previous sections, and also underestimates the vertical extent of the ozone hole, which appears to end at lower altitudes (larger pressures) in MERRA-2 than in MLS. This is reflected also in water vapor, where MERRA-2 fails to reproduce the vertical layering (e.g. July 2015 or July 2017), and appears to underestimate the area of dehydration. (2) The detailed information about the SH winter as shown here for the "conjugate station" will be lost after the end of the last three limb sounders still observing (MLS/AURA, SABER, SMR/ODIN), while for the NH, information will hopefully continue to be available from ground-based MW observations.

These messages have been shown in the revised manuscript to provide a more comprehensive analysis. We state the underestimation of the vertical extent of the ozone hole in MERRA-2 compared to MLS. We explore potential reasons for these discrepancies and discuss the implications for understanding stratospheric dynamics and ozone depletion processes. Additionally, we highlight the potential for ground-based microwave observations to continue providing valuable information for the Northern Hemisphere (NH). We discuss the significance of these observations in providing continuous monitoring capabilities and filling the observational gap left by limb sounders.

Lines 217-218: It is important … I do agree with this sentence. However, this evaluation of GROMOS-C and MIAWARA-C should be discussed much earlier in the paper, before the annual/interannual variability and descent rates are discussed.

The evaluation of GROMOS-C and MIAWARA-C have been discussed in section 3 (Climatology of ozone and water vapor). Please see the reply to the major comment.

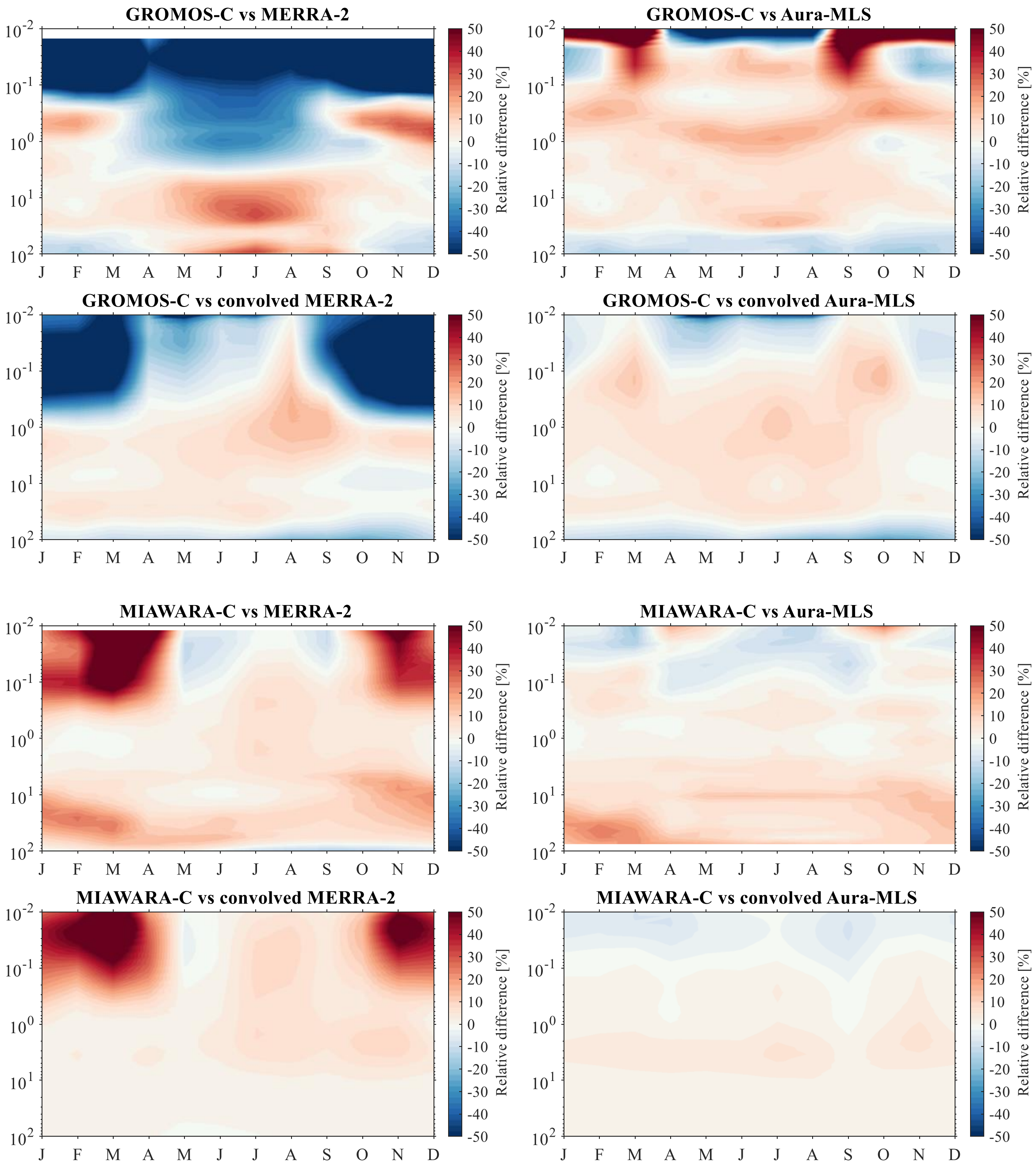
Sections 4.1, 4.2, and 4.3: In general, it would be beneficial to clearly separate the evaluation of the MW data from the data analysis, and to discuss the evaluation first. That is, first discuss the climatologies and their relative differences in the NH, where MW observations are available. Discuss the difference between NH and SH in the next section, then the time-series, and finally the descent rates.

We agree and as suggested by the reviewer, firstly we discuss the climatologies and their relative differences in the NH in section 3 and the time series of ozone and water vapor in section 4 and ascent and descent rates in section 5.

Section 4.3, discussion of Figure 10: is it possible that some of the differences are due to the low vertical resolution of the ground-based MW instruments? That is, could the agreement between MLS and GROMOS/MIAWARA be even better if the MLS data were convolved to the vertical resolution of the GROMOS/MIAWARA observations, e.g., by applying a convolution with the averaging kernels?

Our revision shows MERRA-2 and MLS are convolved with the averaging kernels of GROMOS-C and MIAWARA-C. The vertical resolution of MW instruments is generally coarser compared to satellite limb sounders like MLS, which can result in some differences when comparing the vertical profiles directly. By convolving the MLS data to the vertical resolution of GROMOS-C/MIAWARA-C, we can obtain a better alignment of the observations and assess the level of agreement in a more comparable manner. In the revised manuscript, we will discuss the potential impact of the vertical resolution differences on the observed discrepancies and address the possibility of convolving MLS and MERRA-2 data with the averaging kernels of GROMOS-C/MIAWARA-C.

Here, we show two figures about the relative difference, without the convolution of the averaging kernels and with the convolution of the averaging kernels.



Lines 372-375: I don’t really understand the reasoning here. My understanding of the interhemispheric coupling (based mainly on Körnich and Becker, 2010) is that disturbances are transmitted from the winter stratosphere to the summer mesosphere in the other hemisphere; so a high variability in NH winter downwelling would imply a high variability of SH summer upwelling, which is indeed observed; but also a low variability in the SH winter downwelling would imply a low variability of the NH summer upwelling, however, the converse is observed. I’d say the issue of interhemispheric coupling and how your results relate to that, needs a bit more explanation / discussion.

A high variability in NH winter downwelling would imply a high variability of SH summer upwelling, which is indeed observed in Fig 13. This suggests that the interhemispheric coupling (Körnich and Becker, 2010; Orsolini et al., 2010; Smith et al., 2020a) is that disturbances are transmitted from the winter stratosphere to the summer mesosphere in the other hemisphere. However, it is worth noting that there is a lower variability in SH winter downwelling, which corresponds to a higher variability of NH summer upwelling. This observation suggests that the coupling between the winter and summer circulations within each hemisphere is influenced by various factors beyond the interhemispheric exchange. As shown in Fig 14, with a stronger temperature gradient during SH winter, the polar vortex is relatively stable and well-defined, leading to reduced variability in the downward motion of air (downwelling). For instance, the SSW events during the NH winter (Limpasuvan et al., 2016; Schranz et al., 2019, 2020) or increased stratospheric planetary wave activity (De Wit et al., 2015) lead to increased variability in the NH winter stratosphere.

Line 378: that results in both what?

Changed the sentence as follows: Simulations with a gravity wave resolving model response to the enhanced winter hemisphere Rossby-wave activity could be the mechanism that results in both an interhemispheric coupling through a downward shift of the GW-driven branch of the residual circulation and an increased GW activity at high summer latitudes (Becker and Fritts, 2006).