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Title: Ozone and water vapor variability in the polar middle atmosphere observed with ground-based microwave radiometers

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Review

The paper reports observations of ozone and water vapour (WV) in the stratosphere and mesosphere above Ny-Ålesund, Svalbard using two ground-based microwave radiometers (GROMOS-C and MIAWARA-C). The ~six-year datasets are compared with overlapping satellite observations from the Aura MLS instrument and reanalysis data (MERRA-2). The datasets are used to investigate interhemispheric differences in ozone and WV, with the Arctic location (79 °N, 12 °E) showing greater interannual and seasonal variability in volume mixing ratio (VMR) for both trace gases than at the corresponding southern hemisphere (SH) location (79 °S, 12 °E) above Antarctica. A case is made for using WV profiles as a tracer of vertical transport associated with meridional (residual) circulation, where upwelling occurs above the summer pole and air typically descends in the winter polar vortex. Estimated vertical velocities from the ground-based radiometer (MIAWARA-C) and MLS WV VMR profiles indicate higher variability in atmospheric dynamics and transport at high northern latitudes compared to the SH.

Ozone and WV are important trace gases in the stratosphere and mesosphere, involved in chemical, radiative, and dynamical transport processes. In the polar regions, at latitudes above 60 °N and 60 °S, these species show seasonal variability due to solar UV, atmospheric circulation, polar stratospheric and mesospheric cloud formation, and impacts from space weather and energetic particle precipitation. Understanding these processes requires observations of ozone and WV, which can be made from the ground, balloon, and satellite remote sensing. This paper makes a useful contribution by reporting a new dataset derived from ground-based observations which is compared with satellite data from Aura MLS and meteorological reanalysis data. As the authors point out, satellites measuring middle atmospheric composition are reaching the end of their lifetimes, and ground-based observations such as these complement and extend the long-term datasets.

The main topic areas of the paper – ozone and WV and atmospheric circulation / transport– appear suitable for the journal and special issue. The introduction section is reasonably well written, outlining the relevance of ozone and WV in the polar middle atmosphere and measurement techniques. The results and discussion contain sufficient detail and follow a logical order with fairly clear conclusions. However, the methodology and analysis lack a discussion of measurement errors and uncertainties which is important when comparing datasets. The plotted figures can also be improved. The main issues are expressed in my three major comments. I have identified numerous other areas in the text where improvements and clarifications are needed. My minor comments and suggested edits are listed below the major comments. In conclusion, I recommend a major revision of the paper, with the authors addressing my main comments and each minor point, before the paper is considered further for publication in *egusphere.*

Major comments

1. When comparing datasets from different measurements, it is important to consider measurement and retrieval uncertainties and, for microwave instruments, the choice of a priori data and the effect of limited altitude resolution. Uncertainties in the ozone and WV VMRs from the radiometers and Aura MLS need to be given and considered for example when looking at differences between the observations and reanalysis data. How do the measurement

uncertainties impact on the estimated vertical transport rates? For the microwave instrument retrievals, what effect do the averaging kernels and a priori data have on the retrieved profiles?

2. Although it is suggested (Lines 198–199) that the conjugate latitude station results are lagged by six months relative to those for Ny-Ålesund, that is not the case for the SH plots. It would be very helpful to show the lagged plots. Replotting Figs 4–9 with six-month lags on the SH data will more clearly show the hemispheric differences in seasonal ozone and WV behaviour described at length in the text. The dates or months on the axes need to be adjusted accordingly.
3. Increased ozone abundance at 0.03 hPa / 70 km during winter is incorrectly assigned to the secondary ozone layer (Lines 163–164 and 238–240). The VMR increases are more likely due to the formation of the seasonal tertiary ozone layer which occurs at high latitudes during winter at ~0.03–0.02 hPa / 70–75 km. The secondary ozone layer occurs higher up at ~10^{-2} hPa / 96 km, above the useful range of the datasets presented. As well as making this correction, references to previous tertiary ozone observations need to be added.

<u>Minor comments</u>

Abstract

- Lines 2–6. The two sentences starting 'Leveraging GROMOS-C…' could be shortened or combined, removing repetition.
- Line 3. 'long-term behavior'. Suggest removing this as six years' observations is not particularly long-term, and the focus of the study is the interannual variability of ozone and WV rather than long-term trends.
- Lines 6–7. 'Overall differences… ozone climatology are on the order of 10–15%...'. Rather than 'climatology', state the quantity (volume mixing ratio?) being referred to. Also, can a more precise range be given rather than 'on the order of…'?

1 Introduction

- Line 26. '…summer mesopause temperature up to 100 K away from the…' would be more clearly written as '…summer mesopause temperatures up to 100 K below the…'
- Line 30. '…circulation branch underneath the residual circulation…'. The Brewer Dobson circulation is not immediately beneath the residual circulation. It might be better to write '…circulation branch at altitudes lower than the residual circulation…'
- Line 31 onwards. Brewer-Dobson circulation (BDC) should be defined and the usual abbreviation 'BDC' then used.
- Lines 31–32. 'The Brewer-Dobson Circulation as the major transport pattern in the stratosphere explains the variability of ozone and water vapor.' BDC is a factor in stratospheric ozone and WV variability but, as mentioned later in the manuscript, polar stratospheric clouds can have significant seasonal impacts on ozone and WV abundances in the lower stratosphere.
- Lines 38–39. '…at stratospheric altitudes in the hemispheric winter…' Either give the altitude range or change to e.g., '…in the hemispheric winter stratosphere…'.
- Line 47. '…with the differences…'. Differences in what quantity? Ozone VMR?
- Line 52. '…the air masses dynamic.' Clarify what is meant here.
- Line 55. 'Its distribution…'. State what 'Its' is.
- Line 61. …'column densities, but lack the vertical information.' Column densities are vertical information. Suggest change to '…column densities, but lack vertically-resolved information.'
- Line 68. 'under all weather conditions with a high time resolution of the order of hours except during rain.' Does precipitating or blowing snow affect the observations? A time resolution of

hours might not be considered particularly high – suggest remove the word ‘high’. Do rainy conditions mean that observations cannot be made or that they take longer than hours?

- Line 69. ‘It can be specially designed…’ In what way is a microwave radiometer ‘specially designed’ to measure ozone and WV?
- Line 70. ‘…and provides datasets’. Suggest remove these three words.
- Lines 70–72. The sentence ‘Microwave radiometers can continuously measure the middle atmospheric ozone and water vapor which is valuable as it complements satellite measurements are relatively easy to maintain, and has a long lifetime.’ should probably be ‘Microwave radiometers can continuously measure middle atmospheric ozone and water vapor, which is valuable as it complements satellite measurements, and they are relatively easy to maintain and have long lifetimes.’ How long is a radiometer lifetime?
- Lines 72–73. ‘Ground-based microwave radiometry is the ideal technique to monitor ozone and water vapor in the Arctic/Antarctic middle atmosphere.’ Why is this ‘the ideal technique’ for these measurements?

2.1 GROMOS-C

- Line 91. Suggest change ‘GROMOS-C is designed to be very compact’ to ‘GROMOS-C is very compact’.
- Line 93. Define ‘CO’.
- Lines 95–96. Were ozone profiles retrieved for each of the four cardinal directions or a combined retrieval of the ozone profile vertically above the instrument? How does the GROMOS-C observation geometry compare to the Aura-MLS sampling (Lines 122–123)? Presumably radiometric calibration is performed to obtain ozone spectra. Why is it necessary to average 2 hours data?
- Line 97. Define the abbreviation ‘ARTS’. ‘QPACK’ should be ‘Qpack’ (also on Line108).

2.2 MIAWARA-C

- The observation geometry (azimuthal direction and elevation) needs to be stated and, as for GROMOS-C, compared with the Aura-MLS sampling (Lines 122–123).
- Line 105. ‘The signal’. What signal is being referred to here?
- Line 110. Why is it necessary to average 2-4 hours’ data?

2.3 Aura-MLS

Line 113. Define ‘EOS’.

Line 115. Suggest change ‘MLS scans the limb…’ to ‘MLS scans the atmospheric limb…’.

Line 116. ‘…spaced 1.5 degrees…’. 1.5° in latitude or 1.5° in longitude?

Line 122. Change ‘two times a day’ to ‘twice a day’.

Line 122. ‘location is within ±400 km latitude and ±800 km longitude’. The units of latitude and longitude should be degrees (°). Either give the ± latitude and longitude ranges in ° or change wording to indicate ± km north–south and ± km east–west of Ny-Ålesund.

2.4 MERRA-2

- Line 131. ‘We use the ozone and water vapor with 72 hybrid-eta levels…’. What does ‘hybrid-eta’ mean? State whether MERRA-2 model level or pressure level datasets were used.

3 Time series of ozone and water vapor

- Line 135. 'GROMOS-C and MIAWARA-C perform highly accurate continuous ozone and water vapor measurements…'. Why are the measurements 'highly accurate'? To back this up, statements on the measurement accuracies of each instrument are needed (see also Major comment 1). Also, although the instruments have the potential to make continuous measurements, the data gaps in the plots (e.g., Figure 2(a)) suggest the measurements are at best 'near continuous'. What are the reasons for the measurement data gaps?

3.1 Ny-Ålesund, Svalbard (79 °N, 12 °E) in the NH

- Line 151. '…photo-chemically production…' should be '…photochemical production…'.
- Lines 161–162. 'During late summer and early autumn, stratospheric ozone decreases rapidly when the vortex passes over Ny-Ålesund.' This is incorrect: - the polar vortex occurs in wintertime, not late summer and early autumn.
- Line 163. '…the very big values…'. State the values (see also Major comment 3).
- Line 185. '…water vapor VMR reaches the maximum at 10 hPa.' The 10 hPa pressure level is below the recommended retrieval measurement response (MR) > 0.8 so how well can these values be trusted? Presumably where MR is below 0.8 the radiometer retrievals are driven primarily by the a priori profile. The a priori data used in retrievals from each instrument needs to be stated.
- Line 186. 'In some years,…'. State the years.
- Line 192. 'MERRA2' should be 'MERRA-2' for consistency.

3.2 Conjugate latitude station (79 °S, 12 °E) in the SH

- Lines 198–199. 'For comparison purposes, the conjugate latitude station results are lagged by 6 months relative to those for Ny-Ålesund.' The SH plots in Figs 4-9 are not seasonally lagged but it is recommended that is done (see Major comment 2).
- Line 200. '…ozone VMR maximum of about 6 ppmv in winter and a minimum of about 4 ppmv in summer at about 5 hPa…'. The words 'summer' and 'winter' need to be swapped round.
- Line 207. '…models…' should be '…MERRA-2 data…'.
- Line 211. '…and irreversibly remove water and nitric acid from the upper atmosphere…'. Unclear what the upper atmosphere (i.e., thermosphere and above) has to do with this: - suggest remove the words 'from the upper atmosphere'.

4 Climatologies of ozone and water vapor

- Line 216. 'It is important…' Why is it important?

4.1 Ozone

- Line 227. '…maximum observed and modeled in the SH (approximately 5.5 ppmv) is somewhat smaller and earlier in the season…' Suggest change 'maximum observed and modeled' to 'maximum observed and reanalysis ozone VMR'. Also, smaller by how much, earlier by how much, which season?
- Line 232. 'Polar cap' usually means above the Antarctic land mass or at very high latitude. Suggest change to 'polar region'.
- Line 236. 'The SH…' should be 'The SH ozone VMR…'

4.2 Water vapor

- Line 249. '…relatively long photo-chemical lifetime of water vapor, …'. What is the lifetime?
- Line 251. '…monthly water vapor VMR…' should probably be '…monthly mean water vapor VMR…'.

4.3 Relative differences

- Line 271–279. It would be helpful in the text discussion for this section to refer to the specific panels of Fig. 10 e.g., Fig. 10(a) on Line 271 and Figs 10(b-d) at the relevant places for these panels.

5 Dynamics and transport of water vapor

- Line 300. '…regression fit to different water vapor mixing ratio isopleths…'. State all the isopleth values used here.
- Line 301. 'The time period of 7 years…' For MIAWARA-C the time period appears to be ~six years (2015–2020).
- Line 303. '…dynamic and chemical…'. Dynamic and chemical what?
- Line 309. '…the ascent rate in 2019 and 2020 is slightly earlier…' Rather than 'slightly earlier', quantify how much earlier.
- Line 317. Suggest change '…similar for the 7 years, likely due to the higher stability and stronger of the southern polar vortex.' to '…similar for each of the seven years, likely due to the higher stability and strength of the southern polar vortex.'
- Lines 322–325 and Table 1 (also Discussion and Conclusions sections, also see Major comment 1). The vertical velocities are given to three significant figures, but I wonder whether the linear regression fits are that significant. Would two significant figures suffice? Also, the values only need to be presented once, preferably in Table 1, and discussed in the text. Do the vertical velocities from fits to the different isopleths differ?

6 Discussion

- Lines 350. '…Aura-MLS observations…'. Clarify whether the Aura-MLS temperatures are zonally averaged. How much colder are the southern polar latitudes?
- Line 354. 'There are only a few occasions…' When were these occasions?
- Lines 363–364. 'During this time of the year, horizontal gradients…' What time of year is being referred to here? Horizontal gradient in what?
- Line 380. '…hydroxyl OH…' should be '…hydroxyl (OH)…'.

7 Conclusions

- Lines 388 and 401. 'Ny-Åesund' should be 'Ny-Ålesund'.
- Line 389. 'AURA' should be 'Aura'.
- Line 393. 'satellite observations such as MLS…' should be 'satellite instruments such as MLS…'
- Lines 407 and 409. Mention of the quasi-biennial oscillation (QBO) and climate change, and their relevance to this study, should probably be moved to the Introduction.