Review

General Comments

The paper presents carbon monoxide (CO) measurements in the polar upper stratosphere and mesosphere made using a new ground-based millimetre-wave radiometer (CORAM). Atmospheric observations recorded during the 2017–18 winter from Ny-Ålesund are analysed using optimal estimation retrieval techniques to determine vertical profiles of CO volume mixing ratio. The precision of the measurements is estimated and CORAM profiles are compared with overlapping CO measurements by the Aura MLS satellite instrument.

Measurements of CO in the polar middle atmosphere are important as the gas is sufficiently long-lived to be used as a tracer for characterising dynamical and transport processes associated with the winter-time polar vortex, and atmospheric wave and tide activity. The structure and extent of the polar vortex above Antarctica, and its more dynamic counterpart in the Northern hemisphere affect global circulation patterns, stratospheric ozone abundances, and atmospheric heating rates. Targeted ground-based observations of CO, such as those presented here, complement the much larger geographical coverage of satellite remote sensing datasets. The ground-based instruments provide continuous observations with the potential to resolve features occurring on short timescales.

Overall the paper is reasonably well written and presented, with adequate description of the observations, data-sets, discussion of the results, and citing of prior work. The paper covers the development, inter-comparison, and validation of an atmospheric measurement system and this fits well with the subject areas of the journal. My main criticism is the lack of important details about the CORAM instrument itself. The main novelty in the work is the new design of this radiometer that incorporates optical/electronic components. The authors suggest that this design improves the performance/cost over previous heterodyne radiometers used for this type of measurement. As indicated in my specific comments below, the sections (2.1 and Figure 1) of the paper describing the new instrument need expanding with further technical details. The manuscript would benefit from a more thorough description of existing CO measurement systems including those utilising the thermal IR bands of CO to make middle atmosphere observations. The conclusions section should include clear statements as to how well the anticipated improvements in performance were achieved. I've also identified a number of areas in the text and figures where clarifications are needed and the presentation could be improved. I recommend that the authors address all of these points before the revised paper is considered for publication in *Atmospheric Measurement Techniques*.

Specific Comments

Title

Lines 1–2. It's unclear what the measurement technique is from the title. Perhaps the words 'microwave (or, millimetre-wave) radiometer' could be included in the title?

2.1 CORAM and Figure 1

The technical description of the new instrument is difficult to follow and lacks important details about the novel electronic/optical components. Figure 1 is an unclear, poor quality diagram. It may be better to have two instrument diagrams, one showing the optical layout including the atmospheric and calibration load beam paths, and the other showing the electronic signal chain. For the atmospheric view, why was a 20° elevation chosen and what is the azimuthal angle? What is the field-of-view of the instrument and how far away from the instrument is the observed region of the middle atmosphere? What type of cryocooler is used? How much improvement in SNR is achieved by amplifying the 230 GHz signal by the first-stage LNA, rather than amplification occurring after down conversion to a lower frequency? Has this type of direct amplification been used before? For the FFTS, what alias is used, what is the frequency resolution, and why is this high spectral resolution needed? What baseline SNR is achieved in the recorded spectra? What are the integration times for the calibration and atmospheric signal measurements? Is the instrument located outdoors or inside a building and, if the latter, what external window material was used to transmit the atmospheric signal? What effects do local weather conditions have on the ground-based observations?

Technical Corrections

Abstract

Page 1, line 10. 'CO emissions'. It should be clarified that this refers to CO microwave (or, millimetre-wave) line emissions rather than, e.g. CO emissions from wildfires or industrial production.
Page 1, line 16. The exact start and end dates of the new dataset should be given.

1. Introduction

Page 1, lines 18–23. The authors should make it clear whether they are referring just to microwave (or, millimetre-wave) radiometers or also to other instruments operating at long-wave frequencies to measure thermal emissions from atmospheric molecules. If by 'electronic manipulation' the authors mean the use of heterodyne techniques then that should be clearly stated. Similarly, if 'reliance on the sun' is referring to solar absorption / occultation measurements then that should be made clear.
Page 1, line 26. 'An example of this…' An example of what?
Page 1, line 30. 'allows for more CO-poor air…' should probably be changed to 'allows more CO-poor air…'
Page 2, line 14. 'on smaller timescales…' Smaller than what?
Page 2, line 14. What type of waves are being referred to here?
Page 2, lines 16–17. 'relatively high time resolution'. Relative to what?
Page 2, lines 19–21. A time resolution of ≤1 hr may make the technique well-suited to observe periodic fluctuations in CO. However, the authors should consider how the limited resolution in vertical and horizontal directions would impact on observing structures on varying spatial scales associated with gravity waves, other dynamical processes, and the vortex edge.
Page 2, line 24. The authors should justify why the measurements provide a 'needed increase in Arctic coverage and an excellent opportunity…' How well placed are the Kiruna and Ny-Ålesund instruments for observations near the vortex edge and inside the winter-time Arctic polar vortex?
Page 2, line 25. A reference should be given to sudden stratospheric warmings.

2. Instrument and measured data

2.1 CORAM

Page 3, line 4. Define 'AWIPEV'.

2.2 Inversion method

Page 4, line 7. Define 'WACCM4'.
Page 4, line 7. Presumably data at the WACCM4 grid-point closest to the CORAM observations are used?
Page 4, line 8. '132-layer grid between approximately ground and 130 km altitude'. Why is this a 132-layer (altitude) grid rather than 131 layers (i.e., 0–1 km, 1–2 km, …, 130–131 km)?
Page 4, line 12. 'CO emissions are attenuated by water vapour in the atmosphere'. It should be clarified that attenuation is due to water vapour absorption of the CO signal. Presumably most of the water vapour is in the troposphere?
Page 4, line 14. 'O_3 spectral line lies at 231.28 GHz…' The O_3 line position (i.e. line centre) is at 231.28 GHz.
Page 4, line 15. 'The spectroscopic line data used here is from…' should be changed to 'The spectroscopic line data used here are from…'
Page 4, line 22. 'ECMWF information is available four times per day'. Rephrase to remove any ambiguity, i.e. to make it clear that the ECMWF data are at six hour intervals.
Page 4, line 23. Change 'The temperature data is smoothed…' to 'The temperature data are smoothed…'
Page 4, lines 30–31. Suggest shorten 'Three primary sinusoids were found to be present, …' to 'Three primary sinusoids were found …'
Page 4, line 32. 'large compared with the width of the CO spectral line'. What is the width of the CO spectral line?
Page 5, line 2. Change 'estimated uncertainties of 1 and 0.5 K respectively' to 'estimated uncertainties of 1 K and 0.5 K respectively'.
Page 5, line 5. 'as a fraction of the a priori'. Which a priori?
Page 5, line 5. Change 'due the strong gradients in atmospheric CO' to 'due to the strong gradients in atmospheric CO'. Are the CO gradients in the horizontal or vertical direction, or both?

2.3 CO profile characteristics

Page 5, line 8. 'The instrument required maintenance after this date…' After which date?
Page 5, line 9. The unsmiley symbol on this line should probably be removed.

2.4 CO profile error estimates

Page 6, lines 5–6. 'An uncertainty of 1° is chosen for the pointing of the instrument to the sky, an overestimate of the motor uncertainty…' Could the actual pointing of the instrument be measured rather than relying on an output of the motor positioning mechanism? What is the motor referred to here?
Page 6, line 11. 'uncertainty in the line position is ignored because the frequency grid used in the inversion can be shifted …' Presumably adjusting the frequency grid deals with Doppler line-shifts as well as uncertainty in the line position? Perhaps the wording should be 'is shifted' rather than 'can be shifted'?

3. Comparison with Aura MLS

Page 6, line 24. 'the upper limit of the MLS CO retrieval altitude …' At what altitude is the upper limit?
Page 6, line 25. 'The data has a positive bias in the middle atmosphere, compared to the ACE-FTS satellite instrument, of 20% …' Define 'ACE-FTS'. Change 'The data has …' to 'The data have …' Do you mean that the MLS CO VMR data are 20% higher than the corresponding ACE-FTS data?
Page 6, line 26. 'Pumphrey et al., 2007'. The reference is missing.
Page 6, line 26. 'subsequent versions showing a slight decrease in the CO VMR.' State what are the subsequent MLS CO data versions. Do you mean a slight decrease in CO VMR values or a decrease in the CO VMR bias compared to ACE-FTS? Or perhaps both?

3.1 Colocated measurement comparison

Page 6, line 28. 'MLS measurements are subset to within ±2° latitude and ±10° longitude of CORAM'. Does this latitude/longitude range cover the location of the instrument on the ground and/or the CORAM observations in the middle atmosphere some distance away?
Page 6, lines 28–29. 'The CO VMRs are expected to vary more in latitude than in longitude.' Why is this expected?
Page 6, line 29. 'A longitude space of ±5° was also tested …' should probably be 'A longitude space of ±5° was tested …'
Page 6, line 30 – Page 7, line 1. 'Above 0.001 hPa, MLS CO profiles use a constant VMR value' should be 'Above 0.001 hPa, MLS CO profiles are constant in VMR value' or similar wording.
Page 7, line 10. 'mid-November to mid-January'. Please give the specific dates.
Page 7, line 18. 'The correlation between KIMRA and MLS was slightly higher, …' Slightly higher than the correlation between which other instruments?
Page 7, lines 21–22. 'after which the values become closer in VMR.' Please clarify - do you mean the MLS and CORAM profiles are in better agreement?
Page 7, lines 29 and 31. 'around December 22nd, leading to a local minimum in the first week of January' and 'for about the first 25 hours'. I wonder if the authors could be more exact in the timings?

4. CORAM data and usage

Page 7, line 29. 'decrease in middle-atmospheric CO' should be 'decrease in middle-atmospheric CO VMR'.
Page 8, lines 2–3. 'Over this same time, between 60 and 70 km, there is an oscillation in the 4.1 and 6 ppmv contour lines, with peaks occurring every 1-2 hours.' Please could the authors provide some discussion of possible causes of the observed oscillation.
Page 8, lines 23–24. 'providing the averaging kernels do not significantly change over this time, which would change the measurement response.' Are the averaging kernels likely to change with time, and what might cause such changes?

Conclusion

Page 9, line 1. Suggest change 'CO profiles were retrieved …' to ''CO profiles were retrieved from observations …'
Page 9, lines 1–3. Suggest splitting this rather long sentence into two, e.g. with a full stop after '2017/2018' and starting the next sentence 'Error estimates…' It should be made clear that 'winter' refers to the northern hemisphere / Arctic. It would be worth restating in the conclusion the exact range of measurements dates.
Page 9, lines 6–7. 'abnormally high CO measured by CORAM above ~ 68 km in November' should be rewritten as 'abnormally high CO VMR measured by CORAM above ~ 68 km in November 2017'.

Page 9, lines 9–10. 'November 2017 to January 2018 are currently available.' As suggested above, please give the exact dates for the dataset. How can the available data be accessed?

References

The list of references appears to be sufficiently comprehensive and complete apart from the missing references for Pumphrey et al. (2007) and Kindlmann et al. (2002). However, the list should be carefully checked and correctly formatted by the authors.

Figures and Captions

Figure 2. Are the grid lines needed on the figures? Figure 2(a) should be replotted with a minimum of ~300 K on the receiver noise temperature axis.

Figure 4. 'The measurement response (sum of the rows of the averaging kernels) divided by 4 is shown in solid blue.' There are a number of lines in the plot coloured blue. The colour scheme should be changed or the authors should make it clear whether the measurement response is shown by the thicker blue line.

Figure 5. The axis label 'VMR [ppmv]' should be 'CO VMR [ppmv]'.

Figure 6. The axis labels 'VMR' and 'Δ VMR' should be 'CO VMR [ppmv]' and 'Δ CO VMR [ppmv]' respectively. For Figure 6(d) the correlation scale needs to be changed to make better use of the plot, e.g. the range from 0.7 to 1.0.

Figure 7. Why were the selected altitudes chosen for plotting the time series? The axis labels 'VMR [ppmv]' should be 'CO VMR [ppmv]'. For Figure 7(a) the CO VMR scale should be adjusted to make better use of the plot, e.g. from 12 ppmv to 40 ppmv.

Figure 8. Perhaps the main plot might be clearer with the data gaps shown in white rather than black? Otherwise as presented the narrow black lines due to small data gaps look rather similar to the contour lines. The colourbar labels 'VMR [ppmv]' should be 'CO VMR [ppmv]'. Why were the particular CO VMR values chosen for the contours? The reference to Kindlmann et al. (2002) is missing. What is causing the gaps in the data record?