Anonymous Referee #1

Received and published: 6 September 2017

General Summary:

"This study evaluates the agreement between DIAL profiles, MLS, and CTM in austral spring in Rio Gallegos, Argentina. The material is appropriate for AMT and I have provided some comments below to improve the overall manuscript. Additional references should be added. A location map would improve the understanding of the manuscript in the context of the polar vortex."
Reply: We thank the referee for the effort to carefully reading the manuscript and providing us useful comments. All of the comments are considered properly as listed below. Several references are included properly. A map showing the DIAL observation site in Río Gallegos is also included.

A list below shows differences in Figures after and before this revision.

New	Old
Fig.1: map of Rio Gallegos	
Fig.2: vertical profiles (example)	Fig.1: vertical profiles (example)
Fig.3: time series of DIAL profiles	
Fig.4: sPV maps	
Fig.5: time series (18hPa)	Fig.2: time series (18hPa)
Fig.6: time series (56hPa)	Fig.3: time series (56hPa)
Fig.7: abs diff. vs. sPV diff.	Fig.4: abs diff. vs. sPV diff.
Fig.8: abs diff. vs. MERRA-2 O3 diff.	
Fig.9: abs diff. vs. distance	Fig.5: abs diff. vs. distance
Fig.10: abs/rel diff. vs. prs	Fig.6: abs/rel diff. vs. prs
Fig.11: abs diff. (w/filtered) vs. prs	Fig.7: abs diff. (w/filtered) vs. prs
Fig.12: time series of abs diff. (8hPa)	

Technical Comments:

1. *"A site lat/lon map would improve the discussion in the introduction surrounding the location of the site and vicinity to the polar vortex. Including a map with model/satellite overlay during the case studies would also improve the understanding of the horizontal scale of the variability within the latitude bands of interest."*
Reply: The new Figure 1 shows location of Río Gallegos. We have added a sentence in Section 1 Introduction: "A map showing the OAPA site is shown in Figure 1." A map with model/satellite overlay for one case study on Oct. 3, 2009 is shown in Figure S2. We would like to leave this figure as it is in Supplement.

2. *"P2L27 -It seems you have already evaluated the DIAL, this is more of an evaluation of the MLS/CTM."*
Reply: This DIAL system in Río Gallegos is not extensively evaluated so far (Wolfram et al, 2008; Wolfram et al, 2012). The MLS ozone data have shown the long-term stability and the small bias relative to ozonesonde and ozone lidar (Hubert et al., 2016). Thus, this DIAL ozone data will not be dedicated for validating the MLS ozone data, but the comparison is a good opportunity to evaluate the inter-consistency. On the other hand, the DIAL/MIROC-CTM comparison will be dedicated for evaluating performance of the model in the southern polar vortex season where we have no such a model comparison so far.

3. *"P3L6 -The reference Hubert et al., 2016 is used quite extensively. As DIAL has a very* *robust heritage, consider referring to additional investigators in locations such as this."*

Reply: We have revised these sentences: "DIAL is a laser-based active remote sensing system operated from the ground, aircraft, and ship, and has a robust heritage (e.g., Megie et al., 1977; Browell et al., 1983; Steinbrecht et al., 1989). O3 measurements from DIAL have a high vertical resolution and measurements have shown long-term stability (Nair et al., 2012; Hubert et al., 2016), owing to the stratospheric ozone lidar sites of NDACC (e.g., Leblanc and McDermid, 2000; Brinksma et al., 2002; Godin-Beekmann et al., 2003, Steinbrecht et al., 2009)."

4. *"P3L18-24 -This should be more concisely written as it is very qualitative. Backscatter is from the entire atmosphere, including aerosols. Consider adding in further references."*

Reply: We have revised a corresponding sentence: "The O3 number density profile is computed using the DIAL equation from the difference between the signal slopes originating from Rayleigh scattering of the emitted laser beams (n_{O3}). Since the returned signals include scattering and attenuation by atmospheric molecules, aerosols, and other atmospheric components, this complementary term could be minimized with laser wavelength chosen in the DIAL instrument. The laser wavelength chosen in the DIAL instrument minimizes the complementary term in the stratosphere to less than 10% of n_{O3} measured, in the presence of low aerosol loading (Pelon et al., 1986)."

5. *"P3L28 -'horizontal spatial resolution' – what altitude are you assuming this wind field at? Later on the manuscript interprets differences due to spatial locations, this seems counter to that."*

Reply: This is referred to some typical conditions in the lower stratosphere, so that we have evaluated horizontal distance using an air-parcel trajectory analysis at 83 hPa and summarized in new Table S1. The measurement duration for each date is also summarized in new Table S1. This sentence was revised as: "Most measurements were performed for 3-5 h to obtain a good signal-to-noise ratio (see Table S1 for detailed numbers). If we assume some typical wind speed of 30 m/s in the lower stratosphere, a horizontal spatial resolution becomes 300-500 km. In actual, we have evaluated horizontal distances using air-parcel trajectory analysis at 83 hPa (Tomikawa and Sato, 2005) and the results are summarized in Table S1."

6. *"P3L30 – Total measurement uncertainty – can you describe this more? Does this involve the uncertainty from ozone absorption cross-section, Pulse-pile up, background subtraction? Are you using the retrieved MLS temperature and number density for these comparisons (i.e. ruling out metadata as a source of difference)? Is for a 3 or 5 hour measurement?"*

Reply: We have added sentences in Section 3 Method for comparisons between DIAL and MLS/CTM: "For the total measurement uncertainty (Wolfram et al., 2008), we evaluated the effect of ozone absorption cross section, which is temperature dependent, and found the error is not larger than 2%. The other source is from correction of aerosol contamination. The methodology uses a Fernald inversion algorithm to evaluate the aerosol backscatter signal at 355 nm and extrapolated to 308 nm. In order to increase the signal to noise ratio, the signal registered is averaged over the full acquisition time of the measurement. The acquisition time is typically three to four hours, according to weather conditions. Before processing the signal using the DIAL equation, we make two corrections: 1) subtraction of the background signal using a linear regression within the range of altitudes where the lidar signal is considered negligible, typically between 80 and 150 km; 2) dead time correction of the detector, in order to correct the saturation of the photocounting signals (pile-up effect) in the lower altitude ranges (Godin et al., 1999)."

We do not use MLS temperature and pressure for converting O3 number density to mixing ratio. We used temperature, pressure, and geopotential height of the NCEP reanalysis data (Kalnay et al., 1996) for conversion. Thus, this is another source of uncertainty for the pressure/mixing ratio coordinate comparison. We have added a sentence in Section 3 Method for comparisons between DIAL and MLS/CTM: "For converting the original DIAL geometric altitude and O3 number density to pressure and O3 mixing ratio, the NCEP reanalysis data

(Kalnay et al., 1996) are used. These data are registered in the NDACC database. Possible deviations could be expected if we use other meteorological data for the conversion process in DIAL. However, in this study, we used the DIAL data that registered in the NDACC database."

The actual measurement duration is listed in new Table S1, ranging from 02:24 to 05:45.

7. *"If there is large uncertainty in the DIAL measurements below a certain altitude range, consider removing them from the manuscript."*

Reply: As in new Figure 3, the total error is not so large, but the O3 mixing ratio itself becomes small values in the lowermost stratosphere, providing large relative difference. Thus, we will leave the results of 83 hPa and 100 hPa levels.

8. *"P5L14 – 'In this study step one was not necessary' - then remove this discussion, confusing for reader."*

Reply: We have deleted the corresponding sentences and simply mention as below: "For comparison between DIAL and MLS, the DIAL profile is convolved using the following equation (Livesey et al., 2017): ..."

9. *"P5L16 – specify great circle lat/lon"*

Reply: It becomes between 47.1S and 56.1S for 69.3W. These values were added in the sentence.

10. *"P5L30 – Was eq.1 used or not? If so, revisit this section. If not, drop Eq. 1 entirely from manuscript."*

Reply: Eq. 1 was used. We have revised sentences: "Figure 2a shows vertical profiles of O3 measured with DIAL compared with those of MLS on the same day (November 14, 2009) as an example. The plus-crosses and dotted-line show the converted DIAL profile using Equation (1) and the original high vertical resolution DIAL profile, respectively."

11. *"Fig 1. – I understand the need for the MLS profiles, but are all of the CTM profiles necessary? They seem to cause more confusion and are not even compared in the difference plot. Also, the CTM profiles are significantly different above 10 hPa, this should be discussed."*

Reply: Figure 1 has revised as new Figure 2. CTM profile nearest the OAPA site is shown. We have also revised a corresponding sentence: "We have extracted data from six locations between 48.8S and 54.4S in latitude at 67.5W and 70.3W in longitude, but the nearest grid data was plotted in Figure 2a (see Figures 5 and 6 for the variability in six model grids)."

Above 10 hPa, the deviation of the CTM profile found on November 23, 2009 was actually discussed in Section 4.4 Comparison at other levels. So that, we have added a sentence in the last of Section 4.1 Example of vertical profile comparison: "This is discussed in Section 4.4."

12. *"P6L5 – add in plots of MLS potential temperature in Fig 1 if that is the case"*

Reply: Figure 1 has revised as new Figure 2. The potential temperatures (PT) for MLS computed from the MERRA-2 data are shown as text, instead of plots, for both new Figures 2a and 2b. Corresponding to PT levels of Wolfram et al. (2012), we show 475, 550, 650, and 850 K levels. We have also added a sentence in Section 4.1 Example of vertical profile comparison: "Several PT levels corresponding to pressure are also shown as text in Figure 2a."

13. *"P6L25 – Consider adding in a sentence for the reader to better understand PV and the relationship to the polar vortex. A map of the vortex using scaled PV would be helpful to understand why/where the boundaries were drawn on certain days."*

Reply: We have added a sentence: "The degree of PV values at each measurement or model grid is a robust indicator of the location relative to the polar vortex." sPV maps for selected days are now shown in new Figure 4. Sentences are added in Section 4.2 Time series comparison: "Figure 4 shows sPV maps from MERRA-2 for selected days on September 26, October 3, November 14, and November 23, 2009. At 20 hPa, the polar vortex significantly diminishes on November 23 compared to that on September 26. Whereas at 50 hPa, the polar vortex still exists on November 23 with smaller area than that on September 26."

14. *"Does MIROC-CTM provide a PV product? Is MERRA-2 meteorological variables driving the CTM? If not, couldn't differences in the modeled PV be driving large differences? MERRA-2 provides ozone as well – if this is used, why not compare it as well?"*
Reply: We can compute the PV value from the output of MIROC-CTM, but we used PV values from MERRA-2 for location and time of all DIAL, MLS, and MIROC-CTM in this study to unify the data source. We have performed a model run with MERRA-2 but not achieved a detailed comparison yet (Akiyoshi et al., a presentation in Meteorological Society of Japan, 2017). Since a possible deviation could be expected if we use MERRA-2 for the nudging process in MIROC-CTM, some discussion has added in Section 3 Method for comparisons between DIAL and MLS/CTM: "... Another possible deviations could also be expected if we use other meteorological data for the nudging process in MIROC-CTM. The different reanalysis data may cause different vertical and horizontal motions of air in the model, providing different tracer correlations, hence ozone field. However, in this study, we analyze owing to the model of Akiyoshi et al. (2016) to examine the performance." (See also in Point 6 of Referee#2.)

We have analyzed the O3 value from MERRA-2, and added new Figure 8 and some discussion in Section 4.3 Dependency in distance and sPV difference: "Since the MERRA-2 data set also provide the O3 value (Wargan et al., 2017), we examined those data instead of the sPV value. Figure 8 shows the O3 difference versus MERRA-2 O3 difference between DIAL and MLS (MLS - DIAL). The mean difference is computed from the horizontal axis, resulting in -0.12 ppmv at 18 hPa and -0.02 ppmv at 56 hPa. The measured O3 difference is well reproduced by the MERRA-2 O3 that assimilates Aura MLS as well. At 56 hPa, a compact correlation is found between the two differences with a slope of one-by-one. A similar positive correlation is also found at 18 hPa."

15. *"There is significant vertical motion occurring during the polar vortex breakup, is it worth looking at more vertical levels than just two to evaluate MLS/CTM? Lidar is powerful at analyzing the entire vertical profile. It would be useful to isolate a series of lidar profiles that demonstrate the variability in the polar vortex sPV regimes. Fig 5 highlights the differences that may be associated with horizontal differences, but there is no mention of how the vertical gradients may affect the overall differences between measurements."*
Reply: We have extended discussion on the low bias in MIRCO-CTM above 10 hPa (relate to Point 11). To examine the effect of the vortex breakup on the O3 difference, we have added the O3 difference time series at 8 hPa in new Figure 12. A new Figure 3 shows a series of 23 DIAL profiles. Data are color-scaled based on sPV values. With these figures, we have revised sentences in Section 4.4 Comparison at other levels: summary: "To examine the low bias in MIROC-CTM, the time-series in O3 difference between DIAL and MIROC-CTM at 8 hPa is shown in Figure 12. Larger negative deviations in MIROC-CTM are found in October and November, especially for data with sPV values between -1.0 and -1.5 x 10^{-4} s^{-1}. Similar results are also found from 6 hPa and 7 hPa levels. The peak altitude of ozone in MIROC-CTM is lower than that of DIAL, as shown in Figure 2. Both the vertical and horizontal motions of air in the model are responsible for this different feature, but the cause is not known. As was shown in Figure 3, the vertical gradient of O3 from DIAL above 15-20 hPa shows rather week inside the polar vortex, but occasionally strong outside or edge of the polar vortex. Thus, the vertical gradient of O3 may affect the result for such occasions with the steeper gradient."

Also, we have added a sentence for the new Figure 3 in Section 4.2 Time series comparison: "Figure 3 shows all the 23 profiles of O3 obtained by DIAL. Data are color-scaled based on sPV values. The difference in the O3 value is found depending on the sPV value especially above 30-40 hPa."

Referencers:

Akiyoshi, H., Nakamura, T., Miyasaka, T., Shiotani, M., and Suzuki, M.: A nudged chemistry-climate model simulation of chemical con- stituent distribution at northern high-latitude stratosphere observed by SMILES and MLS during the 2009/2010 stratospheric sudden warming, J. Geophy. Res., 121, 1361–1380, https://doi.org/10.1002/2015JD023334, http://dx.doi.org/10.1002/2015JD023334, 2016.

Brinksma, E. J., Ajtic, J., Bergwerff, J. B., Bodeker, G. E., Boyd, I. S., de Haan, J. F., Hogervorst, W., Hovenier, J. W., and Swart, D. P. J.: Five years of observations of ozone profiles over Lauder, New Zealand, J. Geophys. Res., 107, ACH 18–1–ACH 18–11, https://doi.org/10.1029/2001JD000737, http://dx.doi.org/10.1029/2001JD000737, 2002.

Browell, E. V., Carter, A. F., Shipley, S. T., Allen, R. J., Butler, C. F., Mayo, M. N., Siviter, J. H., and Hall, W. M.: NASA multipurpose airborne DIAL system and measurements of ozone and aerosol profiles, Appl. Opt., 22, 522–534, https://doi.org/10.1364/AO.22.000522, http://ao.osa.org/abstract.cfm?URI=ao-22-4-522, 1983.

Godin, S., Mégie, G., and Pelon, J.: Systematic lidar measurements of the stratospheric ozone vertical distribution, Geophys. Res. Lett., 16, 547–550, https://doi.org/10.1029/GL016i006p00547, http://dx.doi.org/10.1029/GL016i006p00547, 1989.

Godin, S., Carswell, A. I., Donovan, D. P., Claude, H., Steinbrecht, W., McDermid, I. S., McGee, T. J., Gross, M. R., Nakane, H., Swart, D. P. J., Bergwerff, H. B., Uchino, O., von der Gathen, P., and Neuber, R.: Ozone differential absorption lidar algorithm intercomparison, Appl. Opt., 38, 6225–6236, https://doi.org/10.1364/AO.38.006225, http://ao.osa.org/abstract.cfm?URI=ao-38-30-6225, 1999.

Godin-Beekmann, S., Porteneuve, J., and Garnier, A.: Systematic DIAL lidar monitoring of the stratospheric ozone vertical distribution at Observatoire de Haute-Provence (43.92°N, 5.71°E), J. Environ. Monit., 5, 57–67, https://doi.org/10.1039/B205880D, http://dx.doi.org/10.1039/B205880D, 2003.

Hubert, D., Lambert, J.-C., Verhoelst, T., Granville, J., Keppens, A., Baray, J.-L., Bourassa, A. E., Cortesi, U., Degenstein, D. A., Froidevaux, L., Godin-Beekmann, S., Hoppel, K. W., Johnson, B. J., Kyrölä, E., Leblanc, T., Lichtenberg, G., Marchand, M., McElroy, C. T., Murtagh, D., Nakane, H., Portafaix, T., Querel, R., Russell III, J. M., Salvador, J., Smit, H. G. J., Stebel, K., Steinbrecht, W., Strawbridge, K. B., Stübi, R., Swart, D. P. J., Taha, G., Tarasick, D. W., Thompson, A. M., Urban, J., van Gijsel, J. A. E., Van Malderen, R., von der Gathen, P., Walker, K. A., Wolfram, E., and Zawodny, J. M.: Ground-based assessment of the bias and long-term stability of 14 limb and occultation ozone profile data records, Atmos. Meas. Tech., 9, 2497–2534, https://doi.org/10.5194/amt-9-2497-2016, http://www.atmos-meas-tech. net/9/2497/2016/, 2016.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leet- maa, A., Reynolds, R., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Jenne, R., and Joseph, D.: The NCEP/NCAR 40-Year Reanalysis Project, Bull. American Meteorol. Soc., 77, 437–471, https://doi.org/10.1175/1520- 0477(1996)077<0437:TNYRP>2.0.CO;2, https://doi.org/10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2, 1996.

Leblanc, T. and McDermid, I. S.: Stratospheric ozone climatology from lidar measurements at Table Mountain (34.4°N, 117.7°W) and Mauna Loa (19.5°N, 155.6°W), J. Geophys. Res., 105, 14 613–14 623, https://doi.org/10.1029/2000JD900030, http://dx.doi.org/10.1029/2000JD900030, 2000.

Livesey, N. J., Read, W. G., Wagner, P. A., Froidevaux, L., Lambert, A., Manney, G. L., Millán, L. F., Pumphrey, H. C., Santee, M. L., Schwartz, M. J., Wang, S., Fuller, R. A., Jarnot, R. F., Knosp, B. W., and Martinez, E.: Earth Observing System (EOS), Aura Microwave Limb Sounder (MLS), Version 4.2x Level 2 data quality and description document, Version 4.2x-3.0, D-33509, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, https://mls.jpl.nasa.gov/data/datadocs.php, 2017.

Mégie, G., Allain, J., Chanin, M., and Blamont, J.: Vertical profile of stratospheric ozone by lidar sounding from ground, Nature, 270, 329–331, https://doi.org/10.1038/270329a0, 1977.

Nair, P. J., Godin-Beekmann, S., Froidevaux, L., Flynn, L. E., Zawodny, J. M., Russell III, J. M., Pazmiño, A., Ancellet, G., Steinbrecht, W., Claude, H., Leblanc, T., McDermid, S., van Gijsel, J. A. E., Johnson, B., Thomas, A., Hubert, D., Lambert, J.-C., Nakane, H., and Swart, P. J.: Relative drifts and stability of satellite and ground-based stratospheric ozone profiles at NDACC lidar stations, Atmos. Meas. Tech., 5, 1301–1318, https://doi.org/10.5194/amt-5-1301-2012, http://www.atmos-meas-tech.net/5/1301/2012/, 2012.

Pelon, J., Godin, S., and Mégie, G.: Upper stratospheric (30-50 km) lidar observations of the ozone vertical distribution, J.Geophys. Res., 91, 8667–8671, https://doi.org/10.1029/JD091iD08p08667, http://dx.doi.org/10.1029/JD091iD08p08667, 1986.

Steinbrecht, W., Rothe, K. W., and Walther, H.: Lidar setup for daytime and nighttime probing of stratospheric ozone and measurements in polar and equatorial regions, Appl. Opt., 28, 3616–3624, https://doi.org/10.1364/AO.28.003616, http://ao.osa.org/abstract.cfm?URI=ao-28-17-3616, 1989.

Steinbrecht, W., McGee, T. J., Twigg, L. W., Claude, H., Schönenborn, F., Sumnicht, G. K., and Silbert, D.: Intercomparison of stratospheric ozone and temperature profiles during the October 2005 Hohenpeißenberg Ozone Profiling Experiment (HOPE), Atmos. Meas. Tech., 2, 125–145, https://doi.org/10.5194/amt-2-125-2009, https://www.atmos-meas-tech.net/2/125/2009/, 2009.

Tomikawa, Y. and Sato, K.: Design of NIPR trajectory model, Polar Meteorol. Glaciol., 19, 120–137, http://ci.nii.ac.jp/naid/110002261737/en/, 2005.

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, https://doi.org/10.1175/JCLI-D-16-0699.1, 2017.

Wolfram, E. A., Salvador, J., D'Elia, R., Casiccia, C., Leme, N. P., Pazmiño, A., Porteneuve, J., Godin-Beekman, S., Nakane, H., and Quel, J.: New differential absorption lidar for stratospheric ozone monitoring in Patagonia, South Argentina, J. Opt. A: Pure Appl. Opt., 10, 104 021, http://stacks.iop.org/1464-4258/10/i=10/a=104021, 2008.

Wolfram, E. A., Salvador, J., Orte, F., D'Elia, R., Godin-Beekmann, S., Kuttippurath, J., Pazmiño, A., Goutail, F., Casiccia, C., Zamorano, F., Paes Leme, N., and Quel, E. J.: The unusual persistence of an ozone hole over a southern mid-latitude station during the Antarctic spring 2009: a multi-instrument study, Ann. Geophys., 30, 1435–1449, https://doi.org/10.5194/angeo-30-1435-2012, http://www.ann-geophys. net/30/1435/2012/, 2012.