Author comment's

The authors acknowledge to referees and the editor for the time spent to review this manuscript and also for their constructive comments.

This document It is organized as follow:

- point-by-point response to the referee comment's 1: Lucas Vaz Peres.
- point-by-point response to the referee comment's 2: Anonymous.
- marked-up manuscript version.

Point-by-point response to the referee comment's 1: Lucas Vaz Peres

The authors acknowledge to Prof. Lucas Vaz Peres for the time spent to review this manuscript and also for their constructive comments.
The manuscript was revised and improving according the referee comments and suggestions.
Specific answers (in blue) to the referee comments (RC in black) and the modifications into the manuscript (in red) are below.
The number of the page and line of changes is in correspondence with the manuscript version (not with the marked-up manuscript version).

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Interactive comment on "Analysis of an event of short term ozone variation using a Millimiter-Wave Radiometer installed in subpolar region" by Pablo Facundo Orte et al.

Lucas Vaz Peres (Referee)
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Received and published: 23 March 2019

Orte et al., 2019:
"Analysis of an event of short term ozone variation using a Millimiter - Wave Radiometer installed in subpolar region".
General comments:
The authors present a study about an atypical event of polar vortex and ozone hole influence over Río Gallegos during November of 2014. This event was detected from the Millimeter Wave Radiometer (MWR) measurements at 27 and 37 km and the advected potential vorticity (APV) was calculated from the high-resolution advection model MIMOSA (Modélisation Isentrope du transport Mésoéchelle de l'Ozone Stratosphérique par Advection) at 675 and 950 K to understand and explain the atmospheric dynamic related to ozone rapid variation during the passage of the polar vortex. In addition, the MWR dataset were compared for first time with Microwave Limb Sounder (MLS) to 27 km, 37 km and 65 km and with the Differential Absorption Lidar (DIAL) installed in Observatorio Atmosférico de la Patagonia Austral (OAPA) between October 2014 and 2015. This work is a useful representation of the important contribution made by the Millimeter Wave Radiometer (MWR) at Río Gallegos and certainly, understand the ozone hole influence over Río Gallegos is of fundamental importance in many environmental processes which can lead to increases in the UV radiation on the surface. This increase in the UV radiation related to ozone reductions can be dangerous to life on earth and it represent a significant scientific advance. It should be published after some modification as present clearly objectives, if it's the comparison multi-instrument or the ozone reduction study case and precisely discuss the results with the literature (This is the worst article failure). I believe there was a mistake in section 5 Discussion. Because of these I would recommend to accept with Major Revision this manuscript.

Specific comments:

In the abstract:

RC: The abstract must clearly highlight the most significant scientific result, besides first present the main results of comparison between the data sets and after explain the occurrence of the event.

AC: To highlight the results of the study case in the abstract it was improved and the following sentence was inserted in the abstract (marked with bold) (Pg. 1, lines 25-26 and 29-30):

"The measurement shows a very short term recovery in the middle of ozone mixing ratio decrease that could be detected by the MWR.** The advected potential vorticity (APV) calculated from the high-resolution advection model MIMOSA (Modélisation Isentrope du transport Méso-échelle de l'Ozone Stratosphérique par Advection) was also analysed at 675 and 950 K to understand and explain the dynamic at both altitudes and **correlate the ozone rapid recovery measured with the passage of a filament with higher AVP values over Río Gallegos."

The 1. Introduction:

RC: Have a good structure but needs to improve the "historical" contextualization of the scientific problem "ozone transport", documenting it better in the literature.
WAUGH 1993; can be of great value to help in the contextualization of the subject, since that, indirectly, the Ozone Hole can influence the ozone content of medium- and low-latitude regions through the release of polar filaments, which carry air masses of ozone-depleted from the Antarctic polar vortex, causing a temporary decrease in the total ozone column over these regions.
WAUGH, D. W. Subtropical stratospheric mixing linked to disturbances in the polar vortices. Nature, v. 365, p. 535–537, 1993.
Moreover,
KOCH et al., 2002 explain that the extreme anomalies in the total ozone content in mid-latitudes of the stratosphere are associated with the southern transport of regions where the climatological concentrations are lower or higher.
KOCH, G.; WERNLI, H.; STAEHELIN, J.; PETER, T. A Lagrangian analysis of stratospheric ozone variability and long-term trends above Payerne (Switzerland) during 1970–2001. J. Geophys. Res., v. 107, n. D19, p. ACL 2-1–ACL 2-14, 2002.

AC: The introduction is modified (pg. 3, line 19-28) and we add the proposed reference (WAUGH 1993), as follow:

"The air-mass transport in the stratosphere has been extensively analysed using the advected potential vorticity (APV) which is considered a suitable dynamical tracer in the stratosphere. The transport of polar air masses may take the form of "filaments" or "tongue". These terms had been used to explain the transport of air from the edge of the polar vortex into middle latitudes by Waugh (1993) analysing potential vorticity maps, and previously, to explain the intrusion of tropical air into mid-latitudes by Randal et al. (1993). When the intrusion of air from the polar vortex reaches mid-latitudes and produce ozone decreases, it induces anomalies on the surface UV radiation. Bittencourt et al. (2018) also linked the occurrence of this event over South America to later changes in the tropospheric and stratospheric dynamic behaviour. Thus, this parameter can be used to study the dynamics of the Antarctic polar vortex and as a tracer of poor-ozone air masses that are released from the ozone hole (Bittencourt et al., 2018; Kirchhoff et al., 1996, Pinheiro et al., 2011; Wolfram et al., 2012; Hauchecorne et al., 2002; Marchand et al., 2005; Bencherif et al., 2007)."

RC: Objectives should highlight the scientific advance that the article want produces

AC: Paragraph from pg. 3 line 32 to pg. 4 line 8 was improved aiming in highlight the main objectives of this work: Describe the study case, present the capability of the MWR regarding with the high temporal resolution that allows to study short-term ozone variation and present for the first time an inter-comparison with independent ground-based and satellite instruments. These objectives are then reinforced in conclusion section. The paragraph was modified as following:

"In this paper we analyse an unusual event of rapid decrease and recovery of volume mixing ratio over Río Gallegos, Argentina, during November 2014 due to the release of a tongue of a poor-ozone air mass. This analysis was achieved by means of ground and space-based instruments, focusing on the MWR ozone measurements. The high temporal resolution (one hour) of the MWR observations are analysed at different altitudes (27 and 37 km) with the aim to determine the short-term variability of ozone mixing ratio and the moment when the polar vortex and its edge (as tongue or filamentary structure) with poor-ozone air masses pass over Río Gallegos and leave it at those altitudes, resulting in a local peak of ozone mixing ratio for a very short period of time on November 2014. TOC measurements are also analysed by the ground-based instrument SAOZ installed in OAPA and by the satellite Ozone Monitoring Instrument (OMI). Finally, the APV field from the MIMOSA model was used to analyse the air-mass transport during the event. In addition, the MWR ozone mixing ratio retrieved in Río Gallegos is compared for the first time with ground-based measurements from the ozone DIAL/NDACC instrument and satellite measurements from the MLS on board the AURA/NASA."

RC: Pg 2, line 6. Missing reference in this sentence.

AC: Reference was added in the revised manuscript (Pg. 2, line 6):
"Without atmospheric ozone, life would not be possible as we know it today. Although most production takes place in the equatorial region due to the higher level of solar radiation, the maximum ozone concentration is observed over the polar region (Salby, 1996)."

Reference:

- Salby, M. L.: Fund, Atmos. Phys. International geophysics series, Academic Press, Vol. 61, 1996.

RC: Pg 2, line 8. Short paragraph, may be part of the previous paragraph.

AC: Short paragraph was added to the previous paragraph.

RC: Pg 2, line 12. Missing reference in this sentence.

AC: Reference was added (Pg. 2, line 12).

"This ozone destruction is the consequence of human emission of components containing chlorine and bromine into the atmosphere, called Ozone Depleting Substances (ODS) (WMO, 2011)."

Reference:

- World Meteorological Organization (WMO): Scientific Assessment of Ozone Depletion: 2010, Global Ozone Research and Monitoring Project-Report No. 52, 516 pp., Geneva, Switzerland, 2011.

RC: Pg 2, line 17. In the sentence "Its will remain for decades in the atmosphere, destroying ozone on the Antarctic pole" the Artic pole can be inserted.

AC: We agree with this comment, but we want to emphasize on the destruction of the Antarctic ozone which is the phenomenon that is involved in the case study proposed in the manuscript and it is the most important in terms of ozone destruction amount. We decided to include the word "mainly" into the sentence with the intention to reflect that the Antarctic pole is not the only place where ozone destruction may take place, but it is the strongest destruction (pg. 2, line 18-20).

"However, the lifetime of these compounds in the atmosphere is very long (e.g, 100 years for some of them) (M. Rigby et al., 2013, 2014; WMO, 2014) and it will remain for decades in the atmosphere, destroying ozone ***mainly*** *over the Antarctic polar region."*

RC: Pg 3, lines 8 10. “The transport of polar air masses may take the form of “filaments” and “tongue”, which induce anomalies on the ozone and UV observations over mid-latitudes”: Define filament and language in literature. Referring the paragraph in the literature.

AC: This is modified as described above (pg. 3, line 22-31).

RC: Pg 3, line 12. Short paragraph, may be part of the previous paragraph.

AC: Short paragraph was added to the previous paragraph, as suggested.

RC: Pg 3, lines 21 - 28. This paragraph seems to me to be better positioned in the methodology.

AC: The paragraph was improved and moved to section 2 (Materials and Methodology) (pg. 4, line 15).

In the 2. Materials and methods:

RC: 2.1.1 Pg 5, line 3. Define “Glass Dewar”.

AC: The definition of “Glass Dewar” was added (pg.5, line 19).

“The hot blackbody load is achieved using a radio absorber at room temperature (~300 K), while the cold load is achieved by soaking a similar absorber in Liquid nitrogen (77 K) contained in a glass Dewar ***(vacuum bottle made of glass that is used especially for storing liquefied gases).****”*

RC: Pg 5, lines 5 – 6. Short paragraph, may be part of the previous paragraph.

AC: Short paragraph was added to the previous one.

RC: 2.2 It is necessary to show the potential vorticity equation and their terms. Define filaments and tongues observed in the MIMOSA PV fields.

AC: Instead of including the APV equation, reference containing full description of the MIMOSA PV calculation was included (pg 8, line 5).

Reference:

- *Heese, B., S. Godin, and A. Hauchecorne, Forecast and simulation of stratospheric ozone filaments: A validation of a high-resolution potential vorticity advection model by airborne ozone lidar measurements in winter 1998/1999, J. Geophys. Res., 106 (D17), 20011-20024, 2001.*

RC: 2.3 What is the criterion used to identify the occurrence of the polar vortex and ozone hole influence over Río Gallegos? Reduction in ozone and PV values? which? About what?

AC: “Ozone hole influence” is used when the ozone hole is not over Río Gallegos, but there are ozone amount reduction as consequence of the formation of the ozone hole over the Antarctic. The ozone hole is defined by reduction of total ozone column below to 220DU. The identification of the polar vortex (or edge, or filamentary structure or tongue) is obtained by analyzing the APV.
To clarify this point, we modified a paragraph in section 1 (Introduction) (pg. 3, lines 9-13) and the text was reviewed.
Specifically talking about the case study of short-term ozone variation, firstly it is determined the case of rapid variation (decrease or increase) in the ozone mixing ratio by mean of the MWR measurements. Then, analyzing the APV, it is confirmed that the air masses with poor ozone masses are coming from the edge of the polar vortex.

RC: Pg 9, line 2: How was the opacity calculated?

AC: The Opacity Observations is obtained as following:

The radiative transfer equation for microwave remote sensing considering a non scattering and an isothermal medium, can be written as follow (Janssen, 1993):

$$T_b = T\int_0^{\tau_a} e^{-\tau}\ d\tau = T(1 - e^{-\tau_a})$$

where $\mathrm{T_b}$ is the brightness temperature, T is the temperature of the source, and τ_a is the total optical thickness in the optical path of radiation propagation.
In the problems of remote sensing of the atmosphere, $\mathrm{T_b}$ is generally obtained through the measurement and it is desired to infer some component or atmospheric property such as the distribution of ozone for our case, water vapor or temperature.

The observations of the middle-atmosphere with remote sensing techniques from the ground, suffer the extinction of the atmospheric layers that are below, mainly for the troposphere. In the range of micrometer waves, scattering can be neglected. Absorption is produced primarily by water vapor and to a lesser extent, oxygen and other gases. These gases are concentrated in the first kilometers of the atmosphere. Also they emit radiation in the frequency range of measurement, known as continuous emission (if no discrete absorption pick is near to the frequency analyzed).
If we turn away in frequency from the characteristic ozone emission line in the measured radiation spectrum, only we have the contribution of the continuous emission from the troposphere and the absorption can be described by the Beer-Lambert law. Thus, assuming an isotherm troposphere, we can adapt the previous equation to describe the signal from the lower atmosphere for a given angle of observation as:

$$\mathrm{T_{b_{low}}} = \mathrm{T_{trop}}\left(1 - \mathrm{e}^{-\frac{\tau_\mathrm{z}}{\cos(\theta_\mathrm{low})}}\right) + \mathrm{T_{sys}}$$

Where $\mathrm{T_{b_{low}}}$ is the brightness temperature observed by the MWR at θ_low, $\mathrm{T_{trop}}$ is the average temperature of the troposphere, τ_z is the zenith opacity, θ_low the zenith angle of observation and $\mathrm{T_{sys}}$ is the term that describes the instrumental noise. On the other hand, the signal from the hot black body at room temperature will be:

$$\mathrm{T_{hot}} = \mathrm{T_{hot}}' + \ \mathrm{T_{sys}}$$

Where $\mathrm{T_{hot}}'$ is the signal from the hot source in brightness temperature units, without the contribution of system noise. Differentiating these two signals, assuming $\mathrm{T_{trop}} = \mathrm{T_{hot}}'$ and applying natural logarithm on both sides, we have:

$$\ln(\mathrm{T_{hot}} - \mathrm{T_{low}}) = \ln(\mathrm{T_{hot}}') - \frac{\tau_\mathrm{z}}{\cos(\theta_\mathrm{low})}$$

This equation describes a linear relation between the secant of the zenith angle and ln $\ln(\mathrm{T_{hot}} - \mathrm{T_{low}})$ with slope τ_z and intercept $\ln(\mathrm{T_{hot}}')$, which is considered equal to $\ln(\mathrm{T_{trop}})$. Therefore, plotting these observations measure at different directions (Figure below), on the axis x $-1/\cos(\theta)$ and y axis as $\ln(\mathrm{T_{hot}} - \mathrm{T_{low}})$, τ_z and $\mathrm{T_{trop}}$ can be obtained through a linear fit (red line). In this example, an opacity of 0.283 and $\mathrm{T_{trop}} = 407.483$ is obtained. This method is known as "tipping-curve".

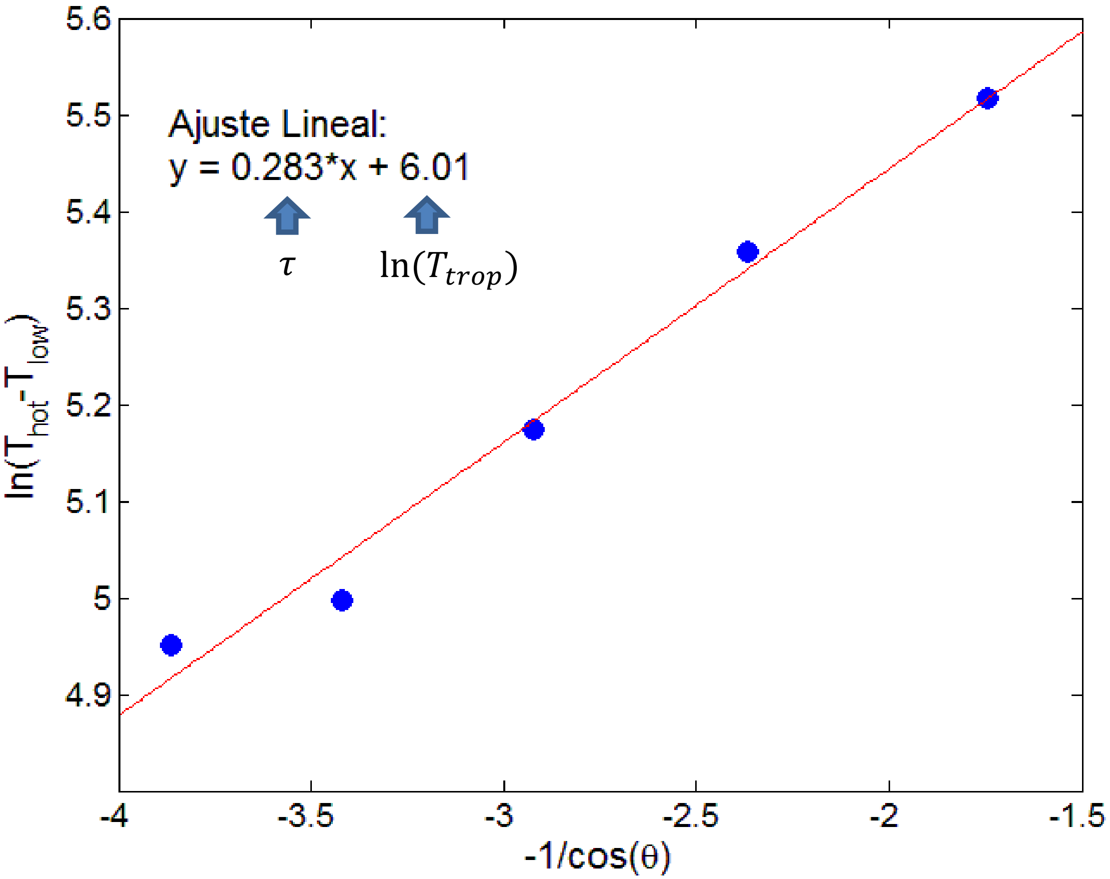

Figure. Example of the retrieval of opacity from MWR observations.

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In the manuscript, we add a sentence mentioning that the opacity is retrieved from the MWR and the reference that describe the procedure to obtain the opacity. The following sentence is added in the manuscript (Pg. 9, line 22):

"The opacity is retrieved by the MWR during the measurement cycle (Orte, 2017)."

The full description of the procedure to obtain the opacity can be found in the reference Orte, 2017, pg.62. It can be found at the following link: http://ria.utn.edu.ar/handle/123456789/20, 2017.

Reference:

- *Orte, P. F.: Procesamiento de señales de un radiómetro de ondas milimétricas para obtener perfiles de ozono y estudios de la radiación solar UV en superficie, PhD Thesis, UTN-FRBA,*http://ria.utn.edu.ar/handle/123456789/20, 2017

RC: Explain better why the heights of 27, 37 and 65 km were chosen to make the comparison.

AC: It was added in subsection 2.3 (Methodological considerations), pg. 8 line 16-22.

In the 3. Inter-comparison of MWR with DIAL system and MLS observations

RC: This section should be within the results

AC: The section “Inter-comparison of MWR with DIAL system and MLS observations” is now adapted and moved to the Result section (please see revised manuscript). (pg. 10, line 4)

RC: Pg 9, line 18. Check the figure number. I think this is 3.1.

AC: In Pg 9, line 18 it is mentioned the Figure 3 (previous version), which is consistent with the text. As there is not figure 3.1, the agreement of all figure numbers were checked to corroborate the consistence in the text.

RC: “This is because the DIAL measurement campaign becomes more intense in those months when the ozone hole approaches southern Argentina.” should be replaced by: “This is because the DIAL measurement campaign becomes more intense in those months when the ozone hole is active and approaches over the southern Argentina”.
Referring the sentence in the literature.

AC: It is replaced by (pg. 10, line 10):

“This is because the DIAL measurement campaign becomes more intense in those months when the ozone hole approaches and overpasses the southern Argentina (Wolfram et al., 2012).”

Reference:

- 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, 2012.

RC: 3.1 Figure 3.1 should be 3.2.

AC: As there is no figure 3.1 and 3.2, the agreements of all figure numbers were checked to corroborate the consistence in the text.

RC: Values of tables 3.1 and 3.2 may be in said figures in order to optimize space.

AC: The values of both tables were merged in one table as following (pg. 27). The text was adapted to the new table:

	Alt.	N	Slope	Intercept [vmr(ppm)]	R	MBE
MWR-MLS	27 km	84	1.01	0.24	0.65	+5%
	37 km	84	0.96	-0.43	0.63	-11%
	65 km	84	0.95	0.02	0.88	-7%
MWR-DIAL	27 km	30	0.93	0.36	0.73	-1%

RC: What criteria are used to call the correlations of considerable (pg 10, line 6), acceptable (pg 10, line 9 and pg 10, line 23), moderate (pg 10, line 10), and very good (pg 10, line 13)?

AC: The criterion used for these words was made taking into consideration the closeness of the correlation coefficient to one. A perfect positive linear correlation is when this value equals one.

We decided to remove the words “acceptable” and “moderate” with the aim to reduce the subjectivity. The paragraph mentioned is modified as follow (pg. 10, line 26):

“Unlike the average ozone mixing ratio at 27 km, the MBE at 37 km reflected an underestimation of ozone mixing ratio of -11% compared with MLS. Fiorucci et al. (2013) also presented differences ranging between -8% and -18 % in the 17–50 km vertical range, reaching ~-18% at 37 km. The regression analysis presents a slope of 0.96 and an intercept of 0.44. Similarly, the correlation coefficient at this altitude was calculated (R = 0.63) to evaluate the correlation between MWR and MLS at this altitude.”

RC: “The MBE was calculated to analyse the bias between satellite and ground-based data. We obtained a value of +5% indicating an MWR overestimation with respect to the MLS”. Validation is usually done from satellite equipment in relation to ground-based equipment, not the reverse as was done here.

AC: The justification of calculate the MBE in this way is that we realize comparisons between measurements with the aim to determine the bias of the MWR respect the MLS and DIAL with the intention that the positive sign reflect an overestimation of the instrument under analysis (MWR) respect others independent instruments (DIAL and MLS), while a negative sign reflecting underestimation. Similar comparisons between these types of instruments where the MWR is analysed in relation of satellite instruments can be found, for example, in Ohyama et al. 2016 or Schneither et al. 2003, among others.

RC: Pg 10, line 9. 11% difference is reliable in the literature.

AC: In literature can be found bigger differences. For example, Fioruchi et al. (2013) reported a difference around 18% at 37 km (from Figure 3), with differences ranging between 8 % to 18 % in the 17–50 km vertical range. Discussion in the literature was added in Discussion section.

RC: Pg 10, line 12. Which represent the slope and intercept values?

AC: In this case, the linear regression is used to evaluate the comparison.
The slope represents how much increase (or decrease) the MWR measurement when the “control” (MLS) measurement increases (or decreases), plus or minus the uncertainty values.
As we have the same desired quantity measured by both instruments inter-compared, the optimal slope will be one. It would indicate that changes in the reliable measurements from the “control” instrument have the same change as the measurements retrieved from the instrument under analysis, plus a random error.
The word “control” is used here to refer the validated instrument (MLS) as a reference.
The same can be said in regard to the intercept estimation. An “optimal” value for the intercept would be 0, indicating no bias from the MWR instrument compared to the reference one (MLS).

RC: The results of this section should be discussed in the literature. This is a major flaw of this article.
- 3.2 Figure 3.5 should be 3.3. The results of this section should be discussed in the literature. This is a major flaw of this article.

AC: There were added the discussion in the literature to evaluate our results in term of the consistence with other results. In addition, the Discussion section (section 4) was improved as we detail below (pg. 13, line 12).

In the 4. Results

RC: 4.1, 4.2 and 4.3. Results are well described but need to be discussed in the literature.

AC: The Discussion section (section 4) was improved in this way. Please, see this section in the revised manuscript.

RC: 4.2. Remove “trend” in pg. 11, line 12 and 21. If you use this term you need to explain how the trend was calculated.

AC: The word “trend” was removed. The phrases were replaced as follow:

Pg.11. line 30: The phrase *“We observe a rapid ozone decrease **trend** at both altitudes from November 11 at 19:30 local time (LT) to November 15”* was replaced by *“We observe a rapid ozone decrease at both altitudes from November 11 at 19:30 local time (LT) to November 15”*

Pg. 12, line 8: The phrase *“The general trend of both measurements follows the behaviour of the MWR at 27 and 37 km and it shows the influence of the ozone hole…” was replaced by “The general behaviour of both measurements follows the behaviour of the MWR at 27 and 37 km and it shows the influence …”*

In the 5. Discussion

RC: This section, in my opinion, should not exist. The results should be discussed as they are described. - I as a reader was anxious for discussion in literature, but I had an unpleasant surprise at seeing only one reference. The way it is, it’s not a discussion.
- Much of what is written in this section can enrich the conclusions.

AC: Attending to this important comment, the discussion section was improved and discussion in literature was added. We present here the paragraphs with large changes:

“In addition to the short-term ozone recovery, during the analysed period was observed reductions as consequence of the ozone hole influence. The ground-based SAOZ and satellite OMI instruments reflected maximum reduction of around 30% in TOC. Similar reduction has been found in Wolfram et al. (2012) during November 2009, while Kirchhoff et al. (1997) had reported maximum reduction of around 60% by 1992-1994 at similar latitudes (Punta Arenas, Chile) respect the monthly mean values. If we analyse the ozone reduction in altitude, we observed maximum decreases of 20% and 25% respect the climatology value at 27 km and 37 km, respectively. DIAL measurements of ozone profiles carried out in the OAPA have shown maximum differences of around 50% in September-November (WMO, 2013; WMO, 2012; WMO, 2011b). These results highlight the importance of measurements at sub-polar regions.”

“The MWR-MLS inter-comparison at 27 km reveals a MBE of 5%, which is consistent with the value obtained Ohyama et al. (2016). Boyd et al. (2007) also carried out similar inter-comparisons between MLS and two MWR installed in Mauna Loa, Hawaii and Lauder, New Zealand. The differences reported for Lauder range from +7% to 10% between ~20 to ~28km, while for Mauna Loa differences are around ~3% (Figure 1, Boyd et al. (2007)). On the other hand, Fiorucci et al. (2013) reported a difference of 10% at 26 km of altitude. Thus, the comparisons carried out between MWR and MLS reveal good agreement for the considered altitudes, consistent with the results of other authors.
Similarly, we analysed the MWR-DIAL comparison at 27 km and we can observe that the correlation coefficient (R = 0.73) and the MBE (1%) are consistent with those obtained by a similar inter-comparison carried out by other authors. Nagahama et al. (1999) obtained a correlation coefficient of 0.77 and a MBE=1%, although that analysis was realized at 38 km. Studer’s et al. results reflect a 1.43% of difference between MWR and DIAL comparison.”

Conclusions

RC: What scientific progress was made in the study?

AC: The conclusion section was improved and the following progresses are mentioned in the Conclusion section:

- The MWR ozone mixing ratio retrieved in Río Gallegos was compared for the first time with ground-based measurements from the ozone DIAL/NDACC instrument and satellite measurements from the MLS on board the AURA/NASA.

- As an example of MWR capability and use, this work focuses on an atypical event of the incursion of polar vortex and ozone hole influence over Río Gallegos, detected from the MWR measurements at 27 km and 37 km during November 2014. The event is then analyzed by the use of Advected Potential vorticity and ground-based and satellite measurements.

- The time series of the ozone mixing ratio with a temporal resolution of ~1 hour from the Millimeter Wave Radiometer (MWR) installed in OAPA, Río Gallegos (51.6º S; 69.3º W) at different altitudes are reported for the first time. Río Gallegos is located in subpolar latitudes, which makes it a suitable site to study stratospheric and mesospheric ozone due to its closeness to the Antarctic ozone hole.

- It is highlighted the importance of these measurements due to the lack of ground-based radiometer observations of ozone between Antarctic latitudes and mid-latitudes, allowing to improve the understanding of the stratospheric and low-mesospheric dynamic using the ozone mixing ratio as a tracer and improving the characterization of the dynamical models.

RC: As tip I suggest to merge what is written in the "Discussion".

AC: The Discussion section was improved considerably as we described above, with the intention to keep this section with discussion in literature as the referee proposed.

References
RC: References - Put in alphabetical order.

AC: Reference was organized in alphabetical order

Figures:
RC: Figure 2.2. Explain in the text why MWR fall data between March and April and July and August.

AC: It was included in the caption of the figure 2.

RC: Figure 5.1 should be in the methodology

AC: The figure was adapted to Material and Methodology section.

Please also note the supplement to this comment:
https://www.ann-geophys-discuss.net/angeo-2019-17/angeo-2019-17-RC1supplement.pdf

Point-by-point response to the referee comment's 2:Anonymous.

The authors acknowledge the anonymous referee for the time spent to review this manuscript and also for their constructive comments.
The manuscript was revised and improving according to the referee comments and suggestions.
Specific answers (in blue) to the referee comments (RC in black) and the paragraph and sentences modified into the manuscript (in green) are below.
The number of the page and line of changes is in correspondence with the manuscript version (not with the marked-up manuscript version).

Interactive comment on "Analysis of an event of short term ozone variation using a Millimiter-Wave Radiometer installed in subpolar region" by Pablo Facundo Orte et al.

Anonymous Referee #2

Received and published: 1 April 2019

Journal: Annales Geophysicae
Revision of MS No.: angeo-2019-17

Title: Analysis of an event of short term ozone variation using a Millimiter-Wave Radiometer installed in subpolar region.
Authors: Pablo Facundo Orte, Elian Wolfram, Jacobo Salvador, Akira Mizuno, Nelson Bègue, Hassan Bencherif, Juan Lucas Bali, Raúl D'Elia, Andrea Pazmiño, Sophie Godin-Beekmann, Hirofumi Ohyama, Jonathan Quiroga.

Overall evaluation

C1

This manuscript analyses an event of polar-vortex-related unusual ozone decreasing at height levels of 27 and 37 km on the stratosphere over Río Gallegos, Argentina, during November of 2014, through a set of remote ground and satellite measurements and dynamical modelling. The subject is appropriate for the scope of Annales Geophysicae. The multiple tools used to analyse the event, and their intercomparison, gives robustness to the work. Results and conclusions imply in general a relevant contribution to the field, given that this type of localized sub-polar ozone reductions, and eventual "mini ozone holes" at lower latitudes, is an atmospheric subject by itself. There are, however, several aspects to revise in order to put the manuscript in conditions to be accepted for publication.

Specific comments:
- The manuscript's title must be as concise and direct as possible, emphasizing the object of study instead one of the used tools. I suggest some like: "Analysis of a November 2014 southern sub-polar short-term ozone variation event". Eventually, if the MWR instrument is cited, please change "Millimiter" by "Millimeter".

AC: We find appropriated the title proposed by the Referee and we make some changes with the intention to include the instrument that allow the "short-term" study over sub-polar regions.
The title was modified as follow:

"*Analysis of a southern sub-polar short-term ozone variation event using a Millimeter-Wave Radiometer*"

RC: A conceptual aspect to revise throughout the manuscript is the coherence and rigor in the use of terms “polar vortex” and “ozone hole”. The “Antarctic polar vortex” is a dynamical phenomenon which has been present probably for millions of years, and their mention is essential when the dynamics is analyzed particularly as a function of the altitude. While, the “Antarctic ozone hole” is the extreme manifestation of the stratospheric ozone layer depletion in the interior of the “Antarctic polar vortex”, which has made evident since late 1970s, and is mainly referred to either when their vertical ozone structure is afforded or their consequences on surface are analysed. To speak of “ozone hole”, for definition the vertical total ozone column values must fall below 220 DU; authors must revise their use when appropriate. In turn, terms as “ozone hole influence” are appropriate for sub-polar regions but in this case explicit mention to the “Antarctic ozone hole” must be made, eventually an abbreviation AOH may be useful. Similarly, phrases as (page 12, lines 19-20) “the southern part of South America has been affected by the systematic and abrupt intrusion of the polar vortex during the spring since the 1980’s” are inappropriate: as said, the Antarctic polar vortex occurs probably since millions years ago, the difference is that before the 1980s their interior produced no “ozone hole”, i.e. ozone values below 220 DU as it is defined, and without the presence of the ozone hole probably the polar vortex intrusions would have no major transcendence for the surface. Authors must take particular care about the use of these key expressions. In this phrase, also the word “systematic” is inappropriate. It could be changed by some like: “the southern part of South America has been affected by the frequent abrupt intrusions of the AOH during the spring since the 1980’s”.
Similarly, the phrase (page 11, line 14) “This decrease is related to the passage of the ozone hole over Rio Gallegos” is wrong, as TOC never falls below 220 DU. Several other paragraphs along the manuscript must be revised accordingly.

AC: The underlined sentences by the reviewer are now changed in the manuscript for better clarification and distinction between AOH influences and AOH overpass.
The introduction was modified to clarify the terms used in the paper as “Ozone hole influence” and “ozone hole overpass”. Please, see pg. 3, lines 11-16.

- Given that the vertical total ozone column (TOC) values are a necessary reference when ozone anomalies are reported, I suggest a detailed mention to the TOC not only when the present case is analysed but also when mention to other cited cases to help distinguish Antarctic ozone hole “influences” from Antarctic ozone hole “overpass”, and ozone hole “reductions” from eventual “mini ozone-holes” or real ozone hole “overpass”.

AC: As we mentioned above, the introduction was modified to clarify the terms used in the paper as “Ozone hole influence” and “ozone hole overpass”. Please, see pg. 3, lines 11-16.

- In the Introduction: as a benchmark for the specific analysis of this work, it would have been desirable a characterization, based on references, of the known springtime typical vertical structure of the atmosphere over southern South America on both “sides” (inner/outer) of the Antarctic ozone hole.

AC: The following paragraph has been added to put in context the ozone reduction due to the ozone hole influence or the ozone hole passing over the southern South America (pg. 2, line 21):

“In spite of the fact that massive ozone depletion is produced over the South Pole, the total ozone column (TOC) and vertical reduction were also observed in non-polar regions between 1980s and 1990s (WMO, 2014). Kirchhoff et al. (1997; 1997b) reported TOC ranging from 145 DU to 250 DU in Punta Arenas (53.0'S, 70.9'W)), during low-ozone events during September-December of 1992-1995, for which the climatological average is 330-334 DU (maximum reduction of ~56%). More recent study reported reduction of 40-45% in TOC over Río Gallegos (Kuttippurath et al. 2010b). ECC (Electro Chemical Cell) ozone-sonde profiles measurements reflect reductions of around 30 to 50% between 15 km to 32 km of altitude in ozone hole condition (inner) respect normal condition (outer the ozone hole) in Punta Arenas (Kirchhoff et al.,1997). Similar reduction was observed from a Differential Absorption Lidar at Río Gallegos (Wolfram et al., 2006).”

- In the same sense, specific parts of these references could be useful to compare and put in major context the results from this work.

AC: Discussion section were improved and references were added to put our results in context with other results. Please, see section 4. Discussion (pg. 13) for more details.

- Given that one of the concerns with ozone negative anomalies is the potential increase in harmful UVB solar irradiance at ground, please could you add, e.g. in Figure 6, other plot of locally-measured clear-sky UV Index (at noon, or at a given fixed solar zenith angle) allowing quantify the simultaneous UVB increase for these days?.

AC: Taking into account this comment, we decided to modify the figure 7 (ex figure 6) adding the daily maximum UVI measured from a ground-based instrument (Radiometer YES UVB-1). This instrument was installed in Río Gallegos by 2014 and it is part of the SAVER-NET radiation network (http://data.savernet-satreps.org/).
We decided to present the daily maximum UVI due to the fact that most of the analysed days were partially cloudy with broken clouds, and the maximum UVI were measured near to the noon.
The daily maximum UVI was added in Figure 7 as follow:

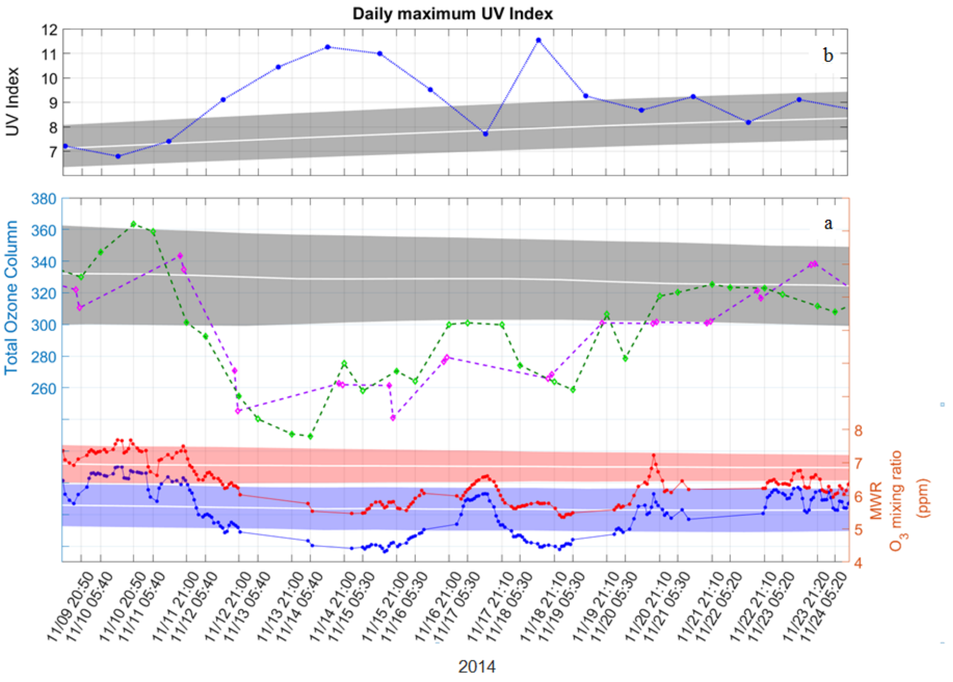

Figure 7. Atypical event of Antarctic ozone hole influence over Río Gallegos. (a) (Bottom) Time evolution of the MWR ozone mixing ratio at 27 km (red line) and 37 km (blue lines). Light red and light blue areas represent the ozone mixing ratio zonal climatology at both altitudes calculated using MLS database (2004 - 2016). (Top) Time evolution of total ozone column measured with the ground-based SAOZ instruments (green dots) and OMI (purple dots) in Dobson Units. White line and grey area represent the climatology and one SD calculated using the OMI data-base (2004 - 2017). (b) Time Evolution of the Daily maximum Ultraviolet Index measured with the ground-based solar radiometer YES UVB-1 at OAPA. White line and grey area represent the climatological UVI at noon in Río Gallegos.

AC: In addition, a paragraph about the description of the daily maximum UVI was added in *3.2.1 Description of the case study* section (pg. 12, line 15).

<u>Minor comments:</u>

Text

- Please define the abbreviations the first time the parameters are mentioned, and then use just the abbreviation. E.g. page 11, line 14: standard deviation is mentioned before, abbreviation SD should be presented the first time it is mentioned and then only SD used. The same for TOC in line 18.

AC: It was revised.

- Page 3, lines 1-2: please change by “due mainly to tropospheric-stratospheric dynamical processes”.

AC: It was changed.

- Page 3, lines 6-10: I think a change in the order of paragraphs would make more coherent this sentence. I suggest: “The transport of polar air masses may take the form of “filaments” and “tongue”, which induce anomalies on the ozone and UV observations over mid-latitudes. Recently, based on satellite and ground-based observations in Uruguay and Southern Brazil, Bresciani et al. (2018) showed a decrease of ozone over these sites during October 2016 in link to this phenomenon”.

AC: Taking into account this comment, the paragraph was changed as following (pg.3, line 22):

“The air-mass transport in the stratosphere has been extensively analysed using the advected potential vorticity (APV) which is considered a suitable dynamical tracer in the stratosphere. The transport of polar air masses may take the form of “filaments” or “tongue”. These terms have been used to explain the transport of air from the edge of the polar vortex into middle latitudes by Waugh (1993) analysing potential vorticity maps, and previously by Randal et al. (1993), to explain the intrusion of tropical air into mid-latitudes. When the intrusion of air from the polar vortex reaches mid-latitudes and produce ozone decreases, it induces anomalies on the surface UV radiation. Bittencourt et al. (2018) also linked the occurrence of this event over South America to later changes in the tropospheric and stratospheric dynamic behaviour. Thus, this parameter can be used to study the dynamics of the Antarctic polar vortex and as a tracer of poor-ozone air masses that are released from the ozone hole (Bittencourt et al., 2018; Kirchhoff et al., 1996, Pinheiro et al., 2011; Wolfram et al., 2012; Hauchecorne et al., 2002; Marchand et al., 2005; Bencherif et al., 2007).”

- Page 3, line 9: “which induce anomalies on the ozone and UV observations”. Anomalies are on the ozone and UV behavior, not on the observations. Please correct.

AC: “UV observations” was change by “surface UV radiation” (pg. 3, line 27).

- Page 3, lines 22-23: phrase “The OAPA is located in sub-polar latitudes, which makes it a suitable site to study stratospheric ozone due to its closeness to the Antarctic ozone hole” is wrong. It could be: “The geographical location of OAPA makes it a suitable site to study the sub-polar stratospheric ozone due to its closeness to Antarctica”.

AC: It was changed as suggested (pg.4, line 18).

- Page 3, line 31: “decreasing the ozone amount” instead “increasing the ozone amount”?.

AC: During the analysed period, decrease and local increase of ozone amount were observed at both altitudes (27 km and 37 km). In this part of the sentence we refer to the local increase, when the ozone mixing ratio at both altitudes (27 km and 37 km) present a local peak.

With the intention to clarify this point in the text, the sentence into the manuscript was changed as follow (pg. 3, line 34):

“The high temporal resolution (one hour) of the MWR observations are analysed at different altitudes (27km and 37 km) with the aim to determine the short-term variability of ozone mixing ratio and the moment when the polar vortex and its edge (as

filamentary structure) with poor-ozone air masses pass over Río Gallegos and leave it at those altitudes, resulting in a local peak of ozone mixing ratio for a very short period of time on November 2014."

- Page 4, some paragraphs of lines 1 up to 8 seem more appropriate for section 2. Materials and Methodology, other for the conclusions and future possibilities. Please redistribute them.

AC: The paragraph was modified and moved to the 2.1 Observations section. (Pg. 4, line 17)

The end of the paragraph was moved to the end of 5. Conclusion section. (Pg. 15 line 20)

- Page 7, line 11: define AMF.

AC: It was replaced by "air mass factor" (pg. 7 line 27)

- Page 8, line 3: "into the daily cycle": did you mean "within the diurnal cycle"?. In line 4: please rewrite "that this gas suffer in this layer" in other form.

AC:
- "into the daily cycle" was change by "within the diurnal cycle" (Pg. 8, line 20).
- The sentence was changed by "We observe a marked difference of ozone mixing ratio between day and night measurements due to the ozone photochemistry around this altitude" (Pg. 8 line 20-21:)

- Page 9, line 22: replace "Argentina" by "South America".

AC: It was replaced (Pg. 10, line 11)

Figures

- Text of Page 11, line 10: . . . "light red". . . but in the caption of Figure 6 it is referred to as "pink".

AC: The color was unified as light red.

- Figure 9 and several paragraphs from the Introduction treating on the characteristics of the measurement site (e.g. page 3, lines 21 on) should be at the start of section 2. Materials and Methodology.

AC:

- Figure 9 (now figure 3) was moved to section 2 (Materials and Methodology) (pg.8, line 28).
- The paragraph describing the measurements site was moved to subsection 2.1 (Observation) and it was adapted as follow (Pg. 4, line 17):

"Ground-based instruments used here are operated at OAPA, Río Gallegos, Argentina (51.5° S; 69.3°W), belonging to CEILAP (hereafter OAPA). The geographical location of OAPA makes it a suitable site to study the sub-polar stratospheric ozone due to its closeness to Antarctica. Since 2005, a Differential Absorption Lidar (DIAL) has been operated at the OAPA with the aim to retrieve stratospheric ozone profiles (Wolfram, 2006; Salvador, 2011), which were joined to the Network for the Detection Composition Change (NDACC) in 2008 (http://www.ndsc.ncep.noaa.gov). In addition, a ground-based SAOZ spectrometer instrument (Pommereau and Goutail, 1988) to retrieve TOC was installed in the OAPA by 2008, which belongs to LATMOS/CNRS. To contribute to ozone monitoring, the Solar Terrestrial Environment Laboratory, Nagoya University, Japan, installed the MWR in OAPA in 2011, which incremented the temporal resolution and increased the altitude range of the ozone profiles (Orte et al., 2011; Orte 2017).

It is important to highlight that the MWR installed in the OAPA is one of few ground-based radiometers able to observe ozone in the southern hemisphere and the unique installed in subpolar regions. In this hemisphere, other ozone radiometers can be found in the Antarctic region in Syowa station and in Halley stations (moved from the Troll station in 2013) (Isono et al., 2014; Daae et al., 2014), and at mid-latitudes, in Lauder, New Zealand (McDermid et al., 1998). The MWR installed in the OAPA, allow to improve the understanding of the stratospheric and low-mesospheric dynamic using the ozone mixing ratio as a tracer and improving the characterization of the dynamical models at this latitudes.

Satellite instrument used here are other useful dataset to measure ozone on global scale and analyse the ozone layer behaviour. In this work, satellite OMI and MLS datasets are used to inter-compare with the ground-based MWR instrument."

- The captions of the figures must contain all the information needed to interpret them.
Please revise the captions of all figures. In Figure 2 please correct . . . ratio for three altitudes: 27, 37 and 65 km.

AC: The captions of all figures were revised and improving. The caption of the figure 2 was corrected.

- The abscissas and ordinates legends and labels must explicit clearly the parameters in each axis. E.g. in Figures 2, 4 and 5, the y-legends must include "ozone mixing ratio".

AC: "Ozone mixing ratio" legend was included in the y-legends of the mentioned figure (now Figure 2, 5 and 6). Also was included in Figure 7 (right axis).

Dates in Figure 3 are better presented in Figure 2.

AC: Date of the mentioned figure was modified.

In Figures 4, 5 the altitude may be in form of title for each plot. In Figure 6 the year is not specified, don't use the abbreviation TOC.
AC:

- The altitude was moved as a title those (Figures now 5 and 6).
- The year was specified at the bottom of the figure (now figure 7) and TOC was changed by "total ozone column"

These comments may be considered as relatively "minor changes". However, I suggest they should be taken as mandatory for a posterior re-evaluation of the manuscript.

Marked-up manuscript version.

The response to the reviews are marked with red color (RC1: Lucas Vaz Perez) and with green color (RC2: Anonimous). The overlap changes are in the red color.

The number of line and page where the changes are made correspond with the manuscript version

Analysis of a southern sub-polar short-term ozone variation event using a Millimeter-Wave Radiometer

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Abstract. Subpolar regions in southern hemisphere are influenced by the Antarctic polar vortex during austral spring, which induces high and short term ozone variability at different altitudes mainly into the stratosphere. This variation may affect considerably the total ozone column changing the harmful UV radiation that reaches the surface.

With the aim to study ozone with high time resolution at different altitudes in subpolar regions, a Millimeter Wave Radiometer (MWR) was installed at the Observatorio Atmosférico de la Patagonia Austral (OAPA), Río Gallegos, Argentina, (51.6° S; 69.3° W) by 2011. This instrument provides ozone profiles with time resolution of ~1 hour which enables studies of short term ozone mixing ratio variability from 25 to ~70 km in altitude. This work presents the MWR ozone observations between October 2014 and 2015 focusing on an atypical event of polar vortex and Antarctic ozone hole influence over Río Gallegos detected from the MWR measurements at 27 and 37 km during November of 2014. The measurement shows a very short term recovery in the middle of ozone mixing ratio decrease that could be detected by the MWR. The advected potential vorticity (APV) calculated from the high-resolution advection model MIMOSA (Modélisation Isentrope du transport Méso-échelle de l'Ozone Stratosphérique par Advection) was also analysed at 675 and 950 K to understand and explain the dynamic at both altitudes and correlate the ozone rapid recovery with the passage of a tongue with low PV values over Río Gallegos. In addition, the MWR dataset were compared for first time with measurements obtained from Microwave Limb Sounder (MLS) at individual altitude levels (27 km, 37 km and 65 km) and with the Differential Absorption Lidar (DIAL) installed in OAPA to analyse the correspondence between the MWR and independent instruments. The MWR-MLS comparison presents reasonable correlation with a mean bias error of +5%, -11% and -7% at 27 km, 37 km and 65 km, respectively. The MWR-DIAL comparison at 27 km presents also good agreement with a mean bias error of -1%.

1 Introduction

Ozone is an atmospheric trace compound, which reaches its absolute maximum concentration in the stratosphere, between 15 and 35km, where it forms the “ozone layer” (London et al., 1985). It acts as an absorber of harmful solar UVB radiation protecting the life on Earth (Salby, 1996, Dobson, 1956). Without atmospheric ozone, life would not be possible as we know it today. Although most production takes place in the equatorial region due to the higher level of solar radiation, the maximum ozone concentration is observed over the polar region (Salby, 1996). This zonal distribution is explained by the Brewer–Dobson circulation (Brewer, 1949; Dobson, 1956), which transports ozone-rich air masses from the Equator to the Pole, into the stratosphere.

Nevertheless, since the 70’s the ozone layer has suffered a drastic reduction over the Antarctic region inside the polar vortex during the austral spring seasons, known as “Antarctic ozone hole” (AOH) (Chubachi, 1984; Farman et al., 1985). This ozone destruction is the consequence of human emission of components containing chlorine and bromine into the atmosphere, called Ozone Depleting Substances (ODS) (WMO, 2011). The most direct impact of ozone reduction is the increase of harmful solar UVB radiation over the surface in polar and subpolar regions (Casiccia et al., 2008; Wolfram et al., 2012).

With the aim to reduce ODS and mitigate ozone depletion, the Montreal Protocol was signed in 1987 banning the use of ODS, and a decrease of these substances in the atmosphere was observed (WMO, 2014). However, the lifetime of these compounds in the atmosphere is very long (e.g, 100 years for some of them) (M. Rigby et al., 2013, 2014; WMO, 2014) and it will remain for decades in the atmosphere, destroying ozone mainly over the Antarctic polar region.

In spite of the fact that massive ozone depletion is produced over the South Pole, the total ozone column (TOC) and vertical reduction were also observed in non-polar regions between 1980s and 1990s (WMO, 2014). Kirchhoff et al. (1997; 1997b) reported TOC ranging from 145 DU to 250 DU in Punta Arenas (53.0'S, 70.9'W)), during low-ozone events during September-December of 1992-1995, for which the climatological average is 330-334 DU (maximum reduction of ~56%). More recent study reported reduction of 40-45% in TOC over Río Gallegos (Kuttippurath et al. 2010b). ECC (Electro Chemical Cell) ozone-sonde profiles measurements reflect reductions of around 30 to 50% between 15 km to 32 km of altitude in ozone hole condition (inner) respect normal condition (outer the ozone hole) in Punta Arenas (Kirchhoff et al.,1997). Similar reduction was observed from a Differential Absorption Lidar at Río Gallegos (Wolfram et al., 2006).

Together with the banning in the use of ODS set by the 1987 Montreal Protocol, the general expectation was that the TOC would recover as the amount of ODS decreased in all regions. Recent studies showed a recovery of the stratospheric ozone column during September (statistically significant) and October (statistically insignificant) for the South Polar Region (Salomon et al., 2016; Weber et al., 2018; Pazmiño et al., 2018). Ground and space-based observations and models have shown an increase of the total ozone since 2000. Nevertheless, this increase is not significant for the period 2000-2013 (WMO, 2014). Ball et al. (2018) extended this period from 1998 to 2016 and concluded that there are non-significant changes in the total amount of ozone from merged ozone datasets.

Recent partial column ozone analysis from satellite ozone composite indicates a decadal increases in the upper stratosphere that is statistically significant (WMO, 2014; Harris et al., 2015; Steinbrecht et al., 2017; Ball et al., 2017; Frith et al., 2017; Ball et al. 2018) attributed in part, to the decline of the ODS. On the other hand, an unexpected decrease of the partial column ozone in lower stratosphere has been suggested, although with a low level of confidence (Nair et al., 2015; Vigouroux et al., 2015; Ball et al., 2018). A global scale study (between 60°N and 60°S) confirmed a significant decrease of partial column ozone in lower stratosphere at tropical latitudes with high level of significance, accounting a continued and uninterrupted decline in the order of ~2.2 DU between 1998 and 2016 (Ball et al., 2018).

During the austral spring time, the Antarctic polar vortex changes its size and shape and it can reach subpolar regions due mainly to tropospheric-stratospheric dynamical processes. Hence, the Antarctic polar vortex can overpass the continental South American region in subpolar latitudes and this situation may provoke decreases in the TOC content to unusual levels due to the passage of masses with low ozone amount, as a consequence of the AOH influence (Pazmiño et al., 2005; Wolfram et al., 2008). The passage of the AOH is identified using the 220 DU threshold, while other considerable reductions in ozone above 220 DU in link to the polar vortex are mentioned as “ozone hole influence”. A particular case of unusual persistence of the AOH influence over southern Argentina was observed during November 2009 with satellite and ground-based instruments, which led to an increase in the risk of UVB radiation on the surface (Wolfram et al., 2012). This phenomenon was first observed by Kirchhoff et al. (1996) and reported by Pinheiro et al. (2011) in South America. Recently, based on satellite and ground-based observations in Uruguay and Southern Brazil, Bresciani et al. (2018) showed a decrease of ozone over these sites during October 2016 in link to overpass of the polar vortex.

The air-mass transport in the stratosphere has been extensively analysed using the advected potential vorticity (APV) which is considered a suitable dynamical tracer in the stratosphere. The transport of polar air masses may take the form of “filaments” or “tongue”. These terms have been used to explain the transport of air from the edge of the polar vortex into middle latitudes by Waugh (1993) analysing potential vorticity maps, and previously by Randal et al. (1993), to explain the intrusion of tropical air into mid-latitudes. When the intrusion of air from the polar vortex reaches mid-latitudes and produce ozone decreases, it induces anomalies on the surface UV radiation. Bittencourt et al. (2018) also linked the occurrence of this event over South America to later changes in the tropospheric and stratospheric dynamic behaviour. Thus, this parameter can be used to study the dynamics of the Antarctic polar vortex and as a tracer of poor-ozone air masses that are released from the AOH (Bittencourt et al., 2018; Kirchhoff et al., 1996, Pinheiro et al., 2011; Wolfram et al., 2012; Hauchecorne et al., 2002; Marchand et al., 2005; Bencherif et al., 2007).

In this paper we analyse an unusual event of rapid decrease and recovery of volume mixing ratio over Río Gallegos, Argentina, during November 2014 due to the release of a tongue of a poor-ozone air mass. This analysis was achieved by means of ground and space-based instruments, focusing on the MWR ozone measurements. The high temporal resolution (one hour) of the MWR observations are analysed at different altitudes (27 km and 37 km) with the aim to determine the short-term variability of ozone mixing ratio and the moment when the polar vortex and its edge (as tongue or filamentary structure) with poor-ozone air masses pass over Río Gallegos and leave it at those altitudes, resulting in a local peak of ozone mixing ratio for a very short period of time on November 2014. TOC measurements are also analysed by the ground-based instrument SAOZ installed in OAPA and by the satellite Ozone Monitoring Instrument (OMI). Finally, the APV field from the MIMOSA model was used to analyse the air-mass transport during the event. In addition, the MWR ozone mixing ratio retrieved in Río Gallegos is compared for the first time with ground-based measurements from the ozone DIAL/NDACC instrument and satellite measurements from the MLS on board the AURA/NASA.

This paper is organized as follows: section 2 describes the ground- and satellite-based ozone instrument, and the MIMOSA model used to calculate APV to determine the origin of air masses over RG. In addition, this section describes the instrumental datasets used in this research and the methodology to analyse the correspondence of the MWR radiometer with respect to the ground based DIAL instrument and the MLS ozone profile at the analysed altitudes. The results of the comparisons are detailed in Section 3. In section 4, the atypical ozone event occurred during November 2014 was analysed at 27 and 37 km with a resolution of one hour determining the rapid variation of ozone mixing ratio over RG.

2 Materials and Methodology

2.1 Observations

Ground-based instruments used here are operated at OAPA, Río Gallegos, Argentina (51.5° S; 69.3°W), belonging to CEILAP (hereafter OAPA). The geographical location of OAPA makes it a suitable site to study the sub-polar stratospheric ozone due to its closeness to Antarctica. Since 2005, a Differential Absorption Lidar (DIAL) has been operated at the OAPA with the aim to retrieve stratospheric ozone profiles (Wolfram, 2006; Salvador, 2011), which were joined to the Network for the Detection Composition Change (NDACC) in 2008 (http://www.ndsc.ncep.noaa.gov). In addition, a ground-based SAOZ spectrometer instrument (Pommereau and Goutail, 1988) to retrieve TOC was installed in the OAPA by 2008, which belongs to LATMOS/CNRS. To contribute to ozone monitoring, the Solar Terrestrial Environment Laboratory, Nagoya University, Japan, installed the MWR in OAPA in 2011, which incremented the temporal resolution and increased the altitude range of the ozone profiles (Orte et al., 2011; Orte 2017).

It is important to highlight that the MWR installed in the OAPA is one of few ground-based radiometers able to observe ozone in the southern hemisphere and the unique installed in subpolar regions. In this hemisphere, other ozone radiometers can be found in the Antarctic region in Syowa station and in Halley stations (moved from the Troll station in 2013) (Isono et al., 2014; Daae et al., 2014), and at mid-latitudes, in Lauder, New Zealand (McDermid et al., 1998). The MWR installed in the OAPA, allow to improve the understanding of the stratospheric and low-mesospheric dynamic using the ozone mixing ratio as a tracer and improving the characterization of the dynamical models at this latitudes.

Satellite instrument used here are other useful dataset to measure ozone on global scale and analyse the ozone layer behaviour. In this work, satellite OMI and MLS datasets are used to inter-compare with the ground-based MWR instrument.

2.1.1 Millimeter Wave Radiometer

The MWR is a fully automated instrument which belongs to Nagoya University. It retrieve ozone profiles ranging from ~25 and ~70 km vertical range with a temporal resolution of the order of one hour, allowing for the study of the short-term variability of this gas. The vertical resolution ranges from ~10 to ~14 km up to 48 km in high, increasing to 16 km above the middle mesosphere.

The MWR system is based on a superheterodyne receiver employing a superconductor-insulator-superconductor (SIS) mixer cooled at 4 K used to convert the ozone signal at ~110.83 GHz down to the intermediate frequency.

The MWR is basically composed of a rotating mirror, a quasi-optical mirror system, a superheterodyne receiver and a spectrometer. Figure 1 shows a scheme of the system installed at the OAPA. The rotating mirror looks toward four directions to acquire the signal from two different zenith angles, S_{low} and S_{high}, and from two known reference blackbody loads to calibrate the signal from voltage to brightness temperature. S_{high} comes from the zenith and it is re-directed to the rotating mirror by a fixed plane mirror, while S_{low} comes from a zenith angle of between 12° and 38°. A dielectric plate is installed through the S_{high} path to increment the continuum levels of the spectrum and then a servosystem is in charge to equalize both signals. A full description of the measurement technique can be found in Mizuno et al., 2002 and Parrish et al., 1988.

The calibration loads consist of two blackbodies at different temperatures, hot and cold. The hot blackbody load is achieved using a radio absorber at room temperature (~300 K), while the cold load is achieved by soaking a similar absorber in Liquid nitrogen (77 K) contained in a glass Dewar (vacuum bottle made of glass that is used especially for storing liquefied gases). The liquid nitrogen is obtained automatically using a compressor-refrigerator of environmental nitrogen. To reduce the standing waves (baseline), a pass length modulator (PLM) is inserted in the signal path which consists of a pair of roof-top mirrors (Mizuno et al., 2002).

The receiver is basically composed of a local oscillator (LO) and the SIS mixer (Ogawa et al., 1990). This system converts the input signal emitted by the atmospheric ozone molecules in their rotational transitions (~ 110,836 GHz) into the lower intermediate frequency (IF~6 GHz). The mixer operates in single side band (SSB) using a wave guide to filter the image band (Asayama et al., 2015) and it is cooled at 4K to reach the superconductive state. This operational temperature improves the signal to noise ratio to obtain a high temporal resolution (~1 hour). The temperature is achieved using a liquid helium closed loop cryogenic refrigerator (DAIKIN CG308, 3-stage GM-JT).

Then, the IF is amplified by a HEMT (High Electron Mobility Transistor) cooled to 15 K. The subsequent components (filters, amplifiers and attenuators) are designed to process the IF signal and fit it to the spectrometer requirements. The spectrometer is a digital FFT (DFS) Acquaris AC240 with 16384 channels and a bandwidth and spectral resolution of 1 GHz and 68 kHz, respectively. Finally, the observed spectrum in brightness temperature is obtained, assuming a linear behaviour among the sky signal ($\mathrm{S_{low}}$ and $\mathrm{S_{high}}$), the hot blackbody signal ($\mathrm{S_{hot}}$) and the cold blackbody signal ($\mathrm{S_{cold}}$) measurements by the following expression:

$$T_{oi} = \frac{T_{hot}-T_{cold}}{S_{hot}-S_{cold}}\left(S_{low} - S_{high}\right), \qquad (1)$$

The method adopted here for the ozone profile retrieval is the optimal estimation method (OEM) described by Rodgers (Rodgers, 2000).

The forward model comparable to the measurement is calculated by means of the Atmospheric Radiative Transfer Simulator (ARTS). Detailed documentation can be found in http://www.radiativetransfer.org/docs /. The Qpack2 (Eriksson, 2005) is a package of Matlab routines used to setup the ARTS model and it has included the OEM calculation for general cases.

The input pressure and temperature for the forward model were obtained combining the NCEP reanalysis data up to ~30km with CIRA climatology above, interpolated for the MWR measurement time and site location. As input a priori ozone profile, we used monthly zonal daytime and night-time MLS O3 climatology between ~15 and 75 km, completed with zonal climatology below and above (McPeters et al., 2012). A full description of the inversion can be found in Orte, 2017.

2.1.2 DIAL (Differential Absorption Lidar)

The ozone DIAL used here was developed by the Centro de Investigación en Láseres y Aplicaciones (CEILAP) in collaboration with the Laboratoire Atmosphères, Milieux, Observations Spatiales (LATMOS; http://www.latmos.ipsl.fr), between 2003 and 2005 (Wolfram, 2006; Salvador, 2011). The ozone profile retrieval algorithms were provided by the Observatory of Haute-Provence (OHP) (Godin, 1987; Godin-Beekmann et al., 2003; Pazmiño, 2003), which were adapted for the DIAL system installed in the OAPA, Río Gallegos (51.6° S; 69.3 ° W) by mid-2005. Since the installation, instrumental and algorithm improvements have been carried out (Salvador, 2011).

DIAL is an active and self-calibrated remote sensing technique similar to radar but using pulses of laser radiation in the ultraviolet range. This instrument requires the emission of two lasers directed to the atmosphere in two different wavelengths: 308 nm (λ_{on}) and 355 nm (λ_{off}). A ClXe excimer laser is responsible for emitting the laser beam at the wavelength λ_{on}, which is absorbed by the atmospheric ozone molecules, while λ_{off} is the reference wavelength produced by the third harmonic of an Nd-YAG laser. The interaction of this laser's radiation with the atmospheric molecules causes scattering following a known spatial distribution, and the photons backscattered in the direction of the instrument are collected by four Newtonian telescopes with a diameter of 50 cm each, which have an aluminized reflective parabolic surface. These photons are reflected and focused on four optical fibers, each located in the focus of each parabolic mirror.

The photons are conducted to a mechanical chopper positioned before the spectrometer to filter the backscattered lidar signal from the bottom of the atmosphere. Finally, a spectrometer is used to separate the backscattered signal at different wavelengths. These signals are then integrated in time (~3 hours) and processed by the retrieval algorithm to obtain ozone profiles. The DIAL instrument covers an altitude range from ~ 15 to ~ 40 km under optimal operating conditions with a vertical resolution between 0.5 and 5 km, depending on the altitude, and it can only operate during clear sky nights. The typical uncertainty associated to this instrument varies between 3 to 15 % from 14 km to 35 km (Wolfram et al., 2012).

2.1.3 AURA satellites: MLS and OMI

The MLS (Microwave Limb Sounder) was launched on July 15, 2004 on board the AURA satellite and it began to operate on August 13, 2004. Since then, this instrument has been able to observe the thermal emission of the atmosphere in the range of submillimeter and millimeter waves. The Earth's limb viewing allows the MLS to achieve a higher altitude resolution (~3 km in the stratosphere and ~5 km in the mesosphere) compared to MWR. A full description of the MLS instrument can be found in Waters et al. (2006). The MLS ozone profiles data versions 3.3 and 3.4 (Livesey et al., 2013) were used (http://mls.jpl.nasa.gov).

The OMI, on board the Aura satellite, started TOC measurements in 2004, with the aim to continue the TOMS satellite record. It was launched in July 2004 in the framework of the Earth Observing System (EOS) project. In addition to ozone, OMI instrument retrieves atmospheric components such as total contents of NO2, SO2, aerosols, among others. This instrument measures the reflected and backscattered solar radiation by an UV-VIS spectrometer with a spectral resolution ranging from ~0.45 to ~0.63nm in nadir view and provides nearly global coverage in one day with a spatial resolution ranging from 13 to 24 km (Levelt et al., 2006). In this work, we used the TOC overpass product from OMI (OMDOAO3). The dataset can be downloaded from https://avdc.gsfc.nasa.gov/index.php?site=2045907950.

2.1.4 SAOZ (Systeme d'Analyse par Observation Zenithale)

The ground-based SAOZ UV-VIS (300 – 650 nm) spectrometer instrument (Pommereau and Goutail, 1988) used in this work was installed in the OAPA observatory in March 11, 2008 and it belongs to LATMOS/CNRS. SAOZ measures the sunlight scattered from the zenith sky. Differential Optical Absorption Spectroscopy (DOAS) method is applied to retrieve total ozone and nitrous dioxide columns twice a day at high solar zenith angles between 86º and 91º at sunrise and sunset. TOC-measurements are performed in the Chappuis visible band (450-550 nm) where ozone cross section are little dependant on temperature. The spectral resolution of the SAOZ installed at Río Gallegos is 0.9 nm. SAOZ retrieval follows UV-Vis NDACC Working Group recommendations: spectral window analysis, absorption cross sections and daily air mass factor to convert measured slant column densities (SCD) in vertical column densities (VCD). In the case of ozone, look-up tables (LuT) of air mass factors are used (Hendrick et al., 2011). The LuT were obtained from the UVSPEC/DISORT radiative transfer model using the TOMS V8 ozone and temperature profiles climatology. This SAOZ joined the NDACC network in 2009 and the dataset can be downloaded from SAOZ webpage (http://saoz.obs.uvsq.fr/SAOZ-RT.html) and NDACC webpage (ftp://ftp.cpc.ncep.noaa.gov/ndacc/station/gallegos/ames/uvvis/).

2.2 MIMOSA Model

The Modélisation Isentrope du transport Méso-échelle de l'Ozone Stratosphérique par Advection (MIMOSA) high-resolution advection model was used here to determine the origin of air masses similar to an isentropic Lagrangian trajectory model. The MIMOSA dynamical model is specifically used to describe filamentary structure through the APV on isentropic surfaces (surface of constant potential temperature) (Hauchecorne, et al., 2002; Godin et al., 2002). The advection is driven by ECMWF meteorological analyses at a resolution of 0.5°x0.5°. It is possible to run the model continuously and follow the evolution of PV filaments for several months. The accuracy of the model has been evaluated by Hauchecorne et al. (2002) and validated against airborne lidar ozone measurements using a correlation between PV and ozone (Heese et al., 2001; Godin et al., 2002; Jumelet et al., 2009). The ability of the MIMOSA model to determine the origin of air masses influencing a given site has been highlighted in several studies (Hauchecorne et al., 2002; Bencherif et al., 2003; Jumelet et al., 2009; Bègue et al., 2017). Moreover, the MIMOSA model is frequently used to detect the origin of air masses inducing laminae on ozone profiles (Hauchecorne et al., 2002; Godin et al., 2002; Portafaix et al., 2003). A full description of this model can be found in Hauchecorne et al., 2002.

2.3 Methodological considerations

Fifteen months of MWR, MLS and DIAL ozone measurements at different altitude over OAPA were analysed, from October 2014 to December 2015. Figure 2 shows the time series of ozone mixing ratio observed by the MWR (blue) and the MLS (red) for altitudes of 27, 37, and 65 km. The first two levels are established in such a way that they are representative of the amount and variability of ozone within the stratosphere, in the dynamic range of the instrument. In addition, around the 37 km occur the maximum of the average ozone mixing ratio for Río Gallegos. The level of 65 km was included to observe the sensitivity of the MWR in the mesosphere within the diurnal cycle. We observe a marked difference of ozone mixing ratio between day and night measurements due to the ozone photochemistry around this altitude (Allen et al., 1984, Nagahama et al., 1999). In general, we can observe that the behaviour of the MWR and MLS measurements for all analysed altitudes is similar.

The MWR has a temporal resolution of ~1 hour, while the MLS presents measurements close to the OAPA with an approximate frequency of one measurement every two days at 19:00 UTC approximately, and two monthly measurements at 5:00 UTC approximately. This frequency is conditioned by the orbit of the AURA satellite. In order to obtain a significant number of profiles to make the comparison, the MLS observations were selected within a box of ±0.2 in latitude and ±5º in longitude from the OAPA location, considering that both instruments were observing the same air mass. Figure 3 shows the position of the MLS measurements selected for the inter-comparison (yellow crosses) and the location of the OAPA (blue dot), where the MWR is located. Numbers below crosses indicates the number of each group of MLS measurements in each location. The time differences between MWR and MLS measurement inter-comparison pairs were less than 30 minutes. Given that MLS measurement are not collocated with the MWR, some differences between instrument could be due to the distance between instruments, mainly during spring when the AOH may influence and produce large difference of ozone mixing ratio in short distances.

While the MWR and the MLS operate automatically, the DIAL requires manual operation in clear sky nights. DIAL monitoring in 2014 and 2015 was intensive during spring (October, November, December) and it was possible to obtain a few measurements if we compare with the high quantity of measurements provided by the MWR and the MLS. The DIAL dataset is not shown in figure 2, but in figure 6 in the next section. For the MWR – DIAL intercomparison pairs we take the MWR measurements in the middle of the ~3 hour integrated interval of the DIAL measurement.

The ozone measurements obtained by the DIAL are in molecules/m3, while the MWR and MLS measurements are in volume mixing ratio. Thus, temperature and pressure from NCEP reanalysis data are then used to convert from molecules/m^3 to volume mixing ratio.

Due to the fact that MLS and DIAL have a better vertical resolution than the MWR, the MLS and DIAL profiles were degraded to the MWR resolution taking into account the averaging kernel functions A, which represent the response of the retrieved ozone profile to the “true” one. The following expression was used to degrade the vertical resolution (Palm et al., 2010):

$$\boldsymbol{x_{LR} = x_a + A(x_{HR} - x_a)} \qquad (2)$$

where, x_{HR} is the MLS or DIAL ozone profile (depending on which instrument is intercompared with the MWR) with the original vertical resolution. x_a and A are the a priori ozone profile and the averaging kernel function used in the MWR inversion, and x_{LR} are the MLS or DIAL ozone profiles degraded to the MWR vertical resolution. Since the ozone DIAL profile is limited in altitude range respect the millimter wave radiometer, it is completed below and above of the measurement with MLS climatologies, interpolated to the OAPA location.

The main source of millimeter wave opacity that impacts radiation coming from ozone molecules in the stratosphere and the mesosphere is water vapour, mainly contained in the troposphere. The opacity is retrieved by the MWR during the measurement cycle (Orte, 2017). Only measurements taken when atmospheric opacity was less than 0.29 were considered. This criterion was defined taking into account the mean value and the variability of the opacity for Río Gallegos, measured by the MWR ($\mu_\tau = 0.225; \sigma_\tau = 0.041$) for the analysed period and studying the correlation between MLS and MWR. We noted that the correlation between MLS and MWR at different altitudes increases when opacity decreases (not presented here).

For evaluating the correspondence between instruments, the mean bias error (MBE) was calculated between the MWR and the DIAL and MLS measurements (x_{LR_A}) for the considered altitudes (27 km, 37 km and 65 km):

$$MBE = 100\ x\ \frac{\overline{MWR_A} - \overline{x_{LR_A}}}{\overline{x_{LR_A}}} \qquad (3)$$

where $\overline{\mathrm{MWR_A}}$ is the average of the MWR ozone mixing ratio at each altitude and $\overline{\mathrm{x_{LR_A}}}$ is the average of the DIAL or MLS measurements at the same altitude.

Finally, a linear regression analysis between each datasets pair at each altitude was performed and the correlation coefficient R was analysed.

3. Results

3.1 Inter-comparison of MWR with DIAL system and MLS observations

With the aim of analysing the correspondence of the MWR with independent instruments, inter-comparisons of ozone mixing ratio respect to the ground-based DIAL instrument and satellite-based MLS were carried out at 27, 37 and 65 km. Figure 4 shows the number of time overlap measurements inter-compared between MWR and MLS (blue bars), and MWR and DIAL (light blue bars) during the period described in Figure 2. A total number of 84 MWR-MLS and 30 MWR-DIAL measurements pairs were inter-compared during the analysed period. The number of MWR-DIAL pairs is larger during spring (Sep-Oct-Nov). This is because the DIAL measurement campaign becomes more intense in those months when the AOH approaches and overpasses the southern South America (Wolfram et al., 2012). Between December 2014 and July 2015, there were no DIAL measurements. On the other hand, we observe that the number of MWR-MLS inter-compared pairs during spring and summer amounting to 59, was larger than that during autumn and winter with 25 pairs. February, March and July do not present inter-compared measurements because few MWR observations were retrieved and did not match MLS observations according to the spatial and temporal overlap criteria defined in the methodology section.

3.1.1 MWR – MLS comparison

Figure 5 (left) shows the time series of the MLS and MWR ozone mixing ratio for 27, 37 and 65 km for measurements when the opacity was less than 0.29 (See Section 2.3). The behaviour of both data series is similar for all altitudes considered. Figure 5 (right) presents the scatter plot between both instruments at different altitudes and the linear regression together with the correlation coefficient (R). Table 1 summarizes the results of the comparisons between datasets.

We compared N=84 MWR – MLS measurements pairs, taking into account the spatial selection criteria according to the location of the MLS measurement with respect to the location of the MWR (LatOAPA ± 0.2°; LongOAPA ± 5°).

The linear regression analysis at 27 km presents a slope of 1.01 and an intercept value of 0.25. The correlation coefficient (R) of 0.65 reflects considerable correlation for both datasets. The MBE was calculated to analyse the bias between ground-based and satellite data. We obtained a value of +5% indicating an MWR overestimation with respect to the MLS.

Unlike the average ozone mixing ratio at 27 km, the MBE at 37 km reflected an underestimation of ozone mixing ratio of -11% compared with MLS. Fiorucci et al. (2013) also presented differences ranging between -8% and -18 % in the 17–50 km vertical range, reaching ~-18% at 37 km. The regression analysis presents a slope of 0.96 and an intercept of 0.44. Similarly, the correlation coefficient at this altitude was calculated (R = 0.63) to evaluate the correlation between MWR and MLS at this altitude.

The best correspondence was found at 65 km. The linear regression presents a slope near to the unity (0.95) with an intercept close to zero (-0.02 ppm). The correlation between measurements was also close to unity (R=0.88), which reflects very good agreement. Finally, a MBE value of -7% shows an underestimation of the average MWR measurements in comparison to MLS.

The difference between measurements can be attributed to the typical uncertainties of each instrument, although another source of difference is introduced due to the non-collocated measurements inter-compared. This point is discussed in section 5.

3.1.2 MWR – DIAL comparison

Figure 6 (left) shows the ozone mixing ratio measured by the MWR and the DIAL for 27 km at the same time, and a comparison between both instruments by mean of a scatter plot (right).

The slope and intercept in the linear regression were 0.93 and 0.36 ppm (~6% of the observed average mixing ratio), respectively, with an acceptable correlation coefficient (R=0.73) (Table 1). This reflects a good agreement between both ground-based instruments at 27 km. Unlike the MWR – MLS inter-comparison at 27 km (R = 0.68), MWR and DIAL instruments are installed at the same place which might explain, in part, the better correlation. The observed discrepancy can be attributed to instrumental uncertainties.

3.2 Short term ozone variability

To study the short term ozone mixing ratio variability related to the AOH influence over Río Gallegos, an extreme event of rapid variation occurred between November 15 and 20, 2014, was analysed using the MWR measurements at 27 and 37 km. A 3 hours running mean was applied.

Zonal ozone mixing ratio climatologies were calculated from the MLS ozone profiles measurements from 2004 to 2016 at both altitudes, interpolated to the latitude of Río Gallegos to analyse differences between measurements and mean values presented at those latitudes.

Finally, the APV was calculated using the MIMOSA model for these altitudes to interpret the ozone measurements.

3.2.1 Description of the case study

After analysing the correspondence of the MWR measurements with independent instruments, here we analyse a short-term ozone variation for an atypical case study of the influence of the AOH over Río Gallegos during on November 2014.

Figure 7a (bottom) shows the time evolution of the MWR ozone mixing ratio at 27 (blue line) and 37 km (red line) by November 2014 with their respective zonal mean value (white line) and one standard deviation (SD) (light blue and light red, respectively). The statistical quantifiers were calculated from the MLS profile dataset, interpolated to the latitude of Río Gallegos from 2004 to 2016. Both altitudes present similar behaviours. We observe a rapid ozone decrease at both altitudes from November 11 at 19:30 local time (LT) to November 15. The minimum value at 27 km is reached at 6:30 LT, while at 37 km it occurs at 5.30 LT, and both minimums are far than two SD from the mean value (around less than 25 and 20% respect the climatology, respectively). This decrease is related to the influence of the AOH over Río Gallegos, followed by a rapid increase reaching a pick on November 17 at 14:30 at both altitudes. At 27 km, the maximum (~6.1 ppm) reaches values above the mean, while at 37 km (~6.6 ppm) it does not reach the mean. After that, the ozone mixing ratio presents a new local valley reaching the minimum on November 19 at 01:30 LT.

Figure 7a (top) also shows the time evolution of TOC from the OMI and the SAOZ installed in the OAPA. The mean value and the SD are depicted by the white line and the shadow area, respectively. We can observe the difference in the frequency of measurements (lower time resolution) with respect to the MWR observations. The general behaviour of both measurements follows the behaviour of the MWR at 27 and 37 km and it shows the influence of the ozone hole on the TOC with a valley from ~November 11 to ~November 22, where the TOC reached unusual values of ~230DU by November 14 (~30% below from climatology) and it is below one SD in the whole mentioned period. The OMI measurements did not present the local atypical maximum described above because its time resolution did not allow observing it. This atypical event is presented in the SAOZ measurement between November 16 at 21:00 and November 17 at 21:00, although the TOC was below one SD from the mean value.

Figure 7b (blue dots) presents the time series of the daily Ultraviolet Index (UVI) maximum (near the noon) during the low ozone event described before measured with a radiometer YES UVB-1 (Yankee Environmental System, Inc.) installed in the OAPA. White line and shadow area are the climatological UVI at noon calculated from the overpass UVI of satellite OMI instrument between 2004 and 2017 for Río Gallegos. As expected, we observe that the UVI presents an opposite behaviour respect the SAOZ and OMI TOC measurements. It is important to note that on November 17 the maximum UVI presents a local minimum value close to the climatology. This local minimum on the maximum UVI could be associated with the short-term ozone recovery observed in the MWR measurement mentioned above (local peak on November 17).

3.2.2 Dynamical context. AOH influence

In order to determine/confirm the polar vortex influence over Río Gallegos and explain the behaviour of the MWR measurement at 27 and 37 km peaking on November 17, the Advected Potential Vorticities (APV) from the MIMOSA model were analysed at 675 K (~27km) and 950K (~37km) for the same period (Figures 8 and 9). Figure 8 show the APV for the Southern Hemisphere to describe the state of the polar vortex at both altitudes and the recovery during a short period from November 11st to 18th, while figure 9 presents the APV over Río Gallegos at both potential temperatures.

On November 11, the polar vortex is out of the continent for both potential temperatures. From November 13rd to December 16th, we observed low values of APV over Río Gallegos, which is correlated with the decrease in ozone amount for the MWR at 27 and 37 km (Figure 7), and with the decrease in the TOC from OMI and SAOZ, due to polar air masses. On the 17th, the APV map shows the formation of a yellow tongue at 675 K reflecting the lower values of APV between ~-39º and ~-43º of latitude over the continent. In the APV map at 950K, some yellow filaments with low APV values can be observed at similar latitudes. We observe that Río Gallegos is out of this tongue and filaments on November 17, and air masses from outside the polar vortex were passing over Río Gallegos. On November 18th, poor ozone air masses reach Río Gallegos again, and the increase of ozone mixing ration at both altitudes is observed in Figure 7.

The APV over Río Gallegos (figure 9) at 675K (~27km) and 950K (~37km) presents a similar behaviour of the MWR measurements at 27 and 37 km. At both altitudes, the APV decreased from November 12nd to 14th, with an increase around 17th, followed by a new decrease on November 18th. For 950 K, the increase before November 17th is smoother than at 675 K, which gives account that the polar vortex at 37 km reached Río Gallegos earlier than at 27 km.

Both analyses in figures 8 and 9 confirm that the polar vortex was retired from Río Gallegos for a short period around November 17th, which explains the local maximum in the ozone mixing ratio detected by the MWR for both altitudes in Figure 7. Thus, the high time resolution of the MWR measurements enables to observe the short term ozone variation and determine the influence of the AOH over Rio Gallegos at each altitude, with a time resolution of one hour, when the atmospheric conditions allow taking measurements.

4. Discussion

It is well known that the southern part of South America has been affected by the frequent abrupt intrusions of the AOH during the spring since the 1980's. As a consequence of this phenomenon, the ozone amount in the middle atmosphere suffers from sudden variations in short time periods of the order of hours. In this paper we presented a case study of short term ozone mixing ratio variability at different isentropic levels over Río Gallegos, Argentina, during November 2014, as consequence of the Polar vortex influence over this region. The study could be conducted thanks to the high time resolution of the MWR instrument used. Other satellite or ground-based instruments that monitor the vertical ozone amount, such as MLS or DIAL, have lower time resolution and they are not able to observe the short term ozone variability. This fact shows the capability of the MWR and the needed to retrieve the ozone mixing ratio at high time resolution to analyse the short-term variability in these regions directly affected by the passage of the polar vortex at different altitudes.

In addition to the short-term ozone recovery, during the analysed period was observed reductions as consequence of the ozone hole influence. The ground-based SAOZ and satellite OMI instruments reflected maximum reduction of around 30% in TOC. Similar reduction has been found in Wolfram et al. (2012) during November 2009, while Kirchhoff et al. (1997) had reported maximum reduction of around 60% by 1992-1994 at similar latitudes (Punta Arenas, Chile) respect the monthly mean values. If we analyse the ozone reduction in altitude, we observed maximum decreases of 20% and 25% respect the climatology value at 27 km and 37 km, respectively. DIAL measurements of ozone profiles carried out in the OAPA have shown maximum differences of around 50% in September-November (WMO, 2013; WMO, 2012; WMO, 2011b). These results highlight the importance of measurements at sub-polar regions.

In sections 3.1, we evaluated the correspondence between the MWR with respect to the MLS at 27 and 37 km and with respect the ground-based DIAL at 27 km. The MWR-MLS inter-comparison at 27 km reveals a MBE of 5%, which is consistent with the value, obtained Ohyama et al. (2016). Boyd et al. (2007) also carried out similar inter-comparisons between MLS and two MWR installed in Mauna Loa, Hawaii and Lauder, New Zealand. The differences reported for Lauder range from +7% to 10% between ~20 to ~28km, while for Mauna Loa differences are around ~3% (Figure 1, Boyd et al. (2007)). On the other hand, Fiorucci et al. (2013) reported a difference of 10% at 26 km of altitude. Thus, the comparisons carried out between MWR and MLS reveal good agreement for the considered altitudes, consistent with the results of other authors.

Similarly, we analysed the MWR-DIAL comparison at 27 km and we can observe that the correlation coefficient (R = 0.73) and the MBE (1%) are consistent with those obtained by a similar inter-comparison carried out by other authors. Nagahama et al. (1999) obtained a correlation coefficient of 0.77 and a MBE=1%, although that analysis was realized at 38 km. Studer's et al. results reflect a 1.43% of difference between MWR and DIAL comparison.

When we compare the MWR with the MLS, it is considered that both instruments are measuring the same air masses, although the location of the satellite measurements differs from the location of the MWR measurements, which can introduce a difference in the ozone mixing ratio measured. These differences could be accentuated during the austral spring, when the AOH occurs, since ozone mixing ratio values can vary considerably over short distances.

At 27 km, we can observe that the correlation between MWR and DIAL (R = 0.73) is better than that between MWR and MLS (R = 0.65) at the same altitude. In addition, the slope for the linear regression analysis reflects a 1% relative difference between MWR and DIAL, while MWR presents a positive bias of 5% with respect to MLS.

One reason why the correspondence between the MWR and the DIAL is greater with respect to the MLS may be that the two instruments installed on the ground (MWR and DIAL) are monitoring the same air mass, while the distance with the location of the MLS observations could be introducing differences in the comparison. Figure 3 shows the position of the 84 MLS measurements analysed (yellow crosses) with respect to the location of the OAPA, where the MWR is located. Numbers below crosses indicates the number of each group of MLS measurements in each location. The maximum distance between measurements reaches ~341 km while the minimum distance is ~23 km with an average distance of 207 km. Only 22% of MLS observations are at a distance less than 100 km from the MWR, while more than 50% of the inter-compared observations are farther than 200 km. Therefore, the distance between the considered location of the MLS measurements and the location of the MWR could explain partly the difference between the ozone mixing ratios retrieved from these two instruments. Comparisons between DIAL and MLS were realized by Sugita et al. (2017) for an unusual case of persistence of the AOH over Río Gallegos occurred during November 2009, who also attributed part of the differences to the non-colocation of the measurements. Future studies analysing longer datasets will be interesting to determine the influence of the distance between measurements on the ozone mixing ratio differences between instruments in this region.

It is important to note that the MWR and DIAL instruments retrieve ozone in different fundamental units. While the MWR provides the ozone mixing ratio, the DIAL provides the ozone number density as a function of altitude. The DIAL unit was converted to the MWR unit for the inter-comparison using the temperature and pressure retrieved from the DIAL. Thus, uncertainties in these parameters could be adding uncertainties in the ozone amount in ppm from the DIAL.

5. Conclusion

We have presented ozone mixing ratio measurements at 27, 37 and 65 km with a temporal resolution of ~1 hour from a Millimeter Wave Radiometer installed at Río Gallegos, Argentina, from October 2014 to December 2015.

The MWR ozone mixing ratio retrieved was compared for the first time with ground-based measurements from the ozone DIAL instrument and satellite measurements from the MLS on board the AURA in defined overlap altitudes. The comparison revelled good correspondence between independent instruments. The comparison with MLS measurements presents a positive bias of 5% at 27 km and a negative bias of -11% and -7% at 37 and 65 km, respectively. The correlation between measurements at those altitudes was 0.65, 0.63 and 0.88 at 27, 37 and 65 km, respectively. The comparison with the DIAL data at 27 km reflected a good correspondence with a negative bias of -1% with a correlation coefficient of 0.73.

We observed better correspondence between MWR and DIAL at 27 with respect the MWR-MLS. One reason of this better correspondence may be that the two instruments installed on ground (MWR and DIAL) are monitoring the same air mass, while the distance with the location of the MLS observations could be introducing differences in the comparison.

Moreover, this work highlights the capability of the MWR installed in Río Gallegos for the determination of short-term variations of the ozone mixing ratio at different altitudes in this strategic location at the edge of the AOH, making it possible to detect the influence of this phenomenon as we showed in the atypical study case held on November, 2014. The rapid variation of ozone at 27 and 37 km was analysed in correspondence with the perturbation of the APV derived from the MIMOSA model which explain the volume mixing ratio peak due to the retired of the polar vortex for a short time on November 17. The time evolution of the daily maximum UVI measurements during the analysed period, clearly reflect the anti-correlation with the TOC.

The MWR installed in the OAPA cover the lack of ground-based radiometer observation of ozone between Antarctic latitudes and mid-latitudes, allowing to improve the understanding of the stratospheric and low-mesospheric dynamic using the ozone mixing ratio as a tracer and improving the characterization of the dynamical models. It is expected to join the MWR to the NDACC Network in future.

Acknowledgement

This work was supported by the French-Argentine ECOS-Sud A16U01 project. The authors would like to thank to JICA and JST for the financial support of SAVER-Net network and OAPA facilities in South of Argentina. Also, thanks a lot to the referees for their valuable comments which helped to improve the manuscript.

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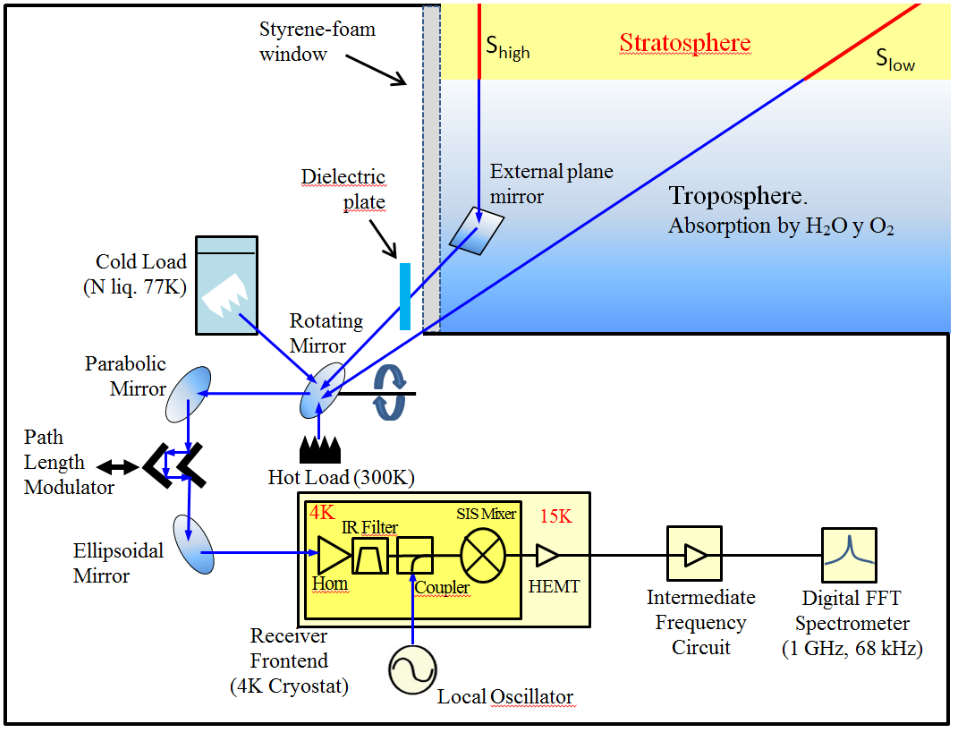

Figure 1 Block diagram of the MWR at the OAPA, Río Gallegos (51.6°S, 69.3°W).

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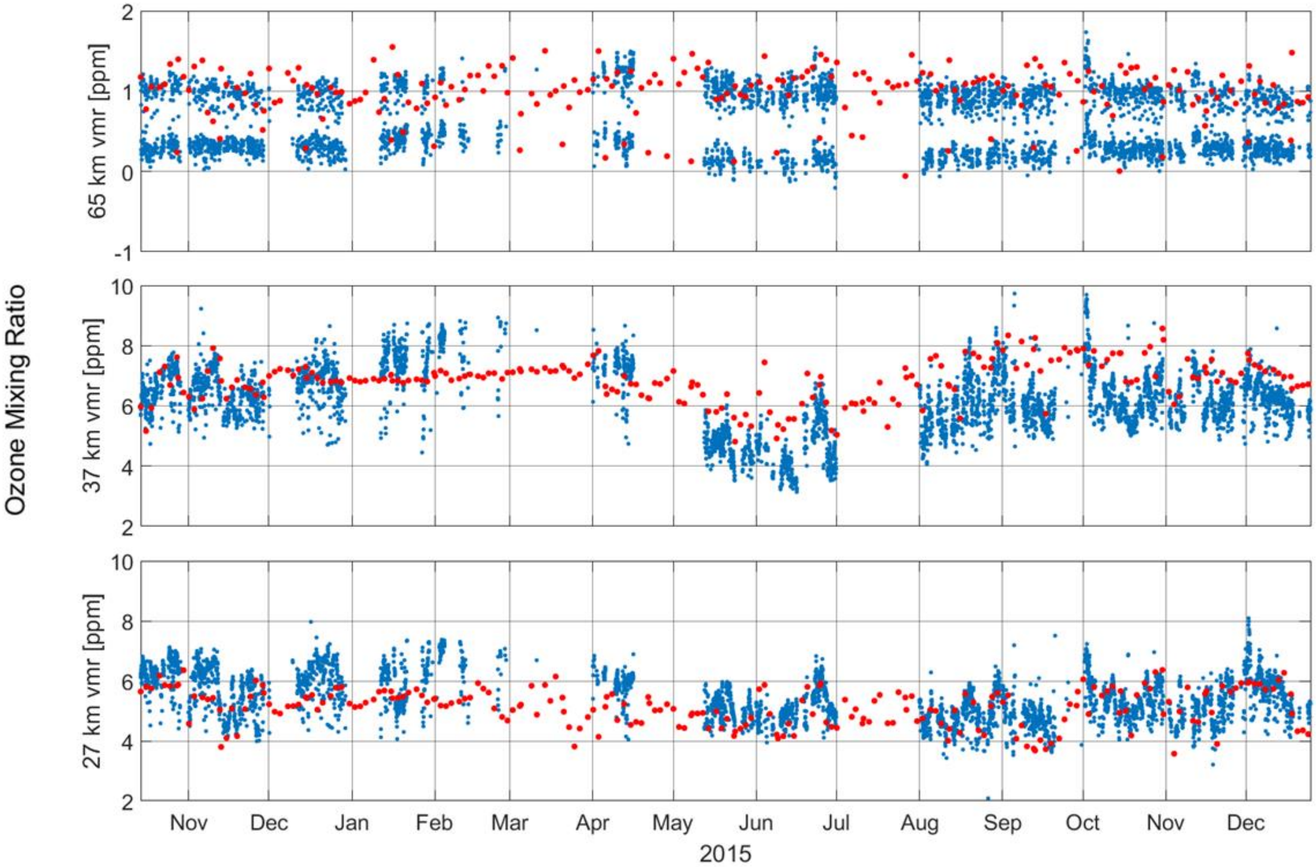

Figure 2 Time series of MLS (red dots) and MWR (blue dots) ozone mixing ratio for three altitudes: 27, 37 and 65 km between October 2014 and December 2015 (the MWR was inoperative during March and July 2015 due to technical problems).

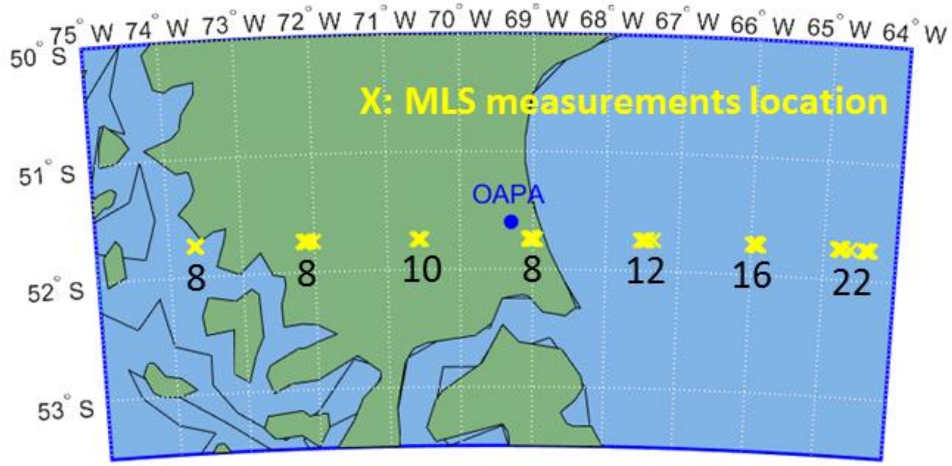

Figure 3 MWR location (blue dot, OAPA) and MLS measurements location (yellow crosses) used in the inter-comparison. The numbers below crosses indicates the quantity of MLS measurements.

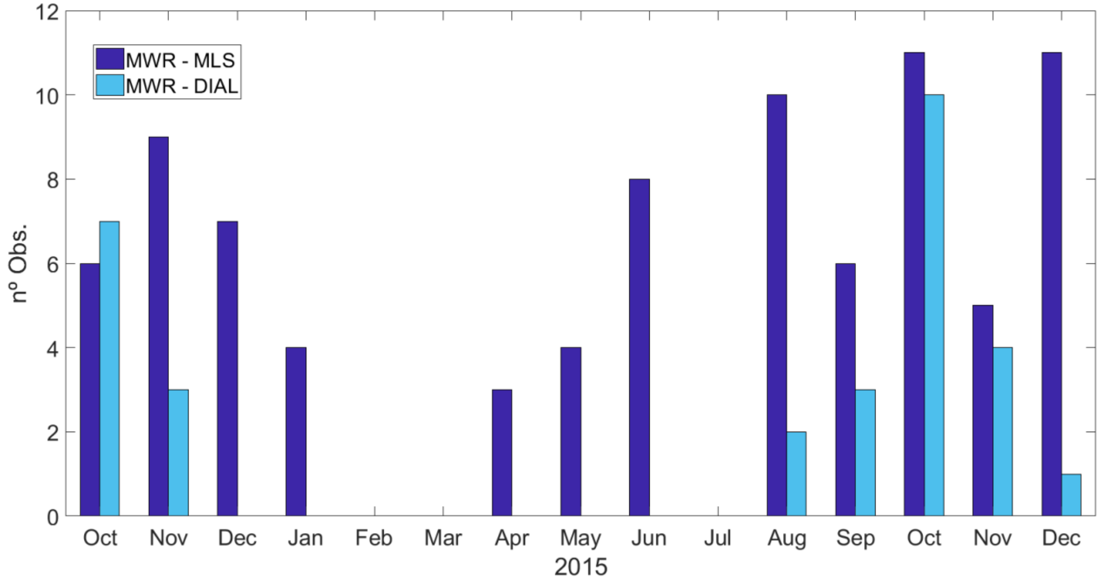

Figure 4 Number of inter-compared measurement pairs for each month. Blue bars represent the number of MWR-MLS pairs while light blue bars are the number of MWR-DIAL pairs.

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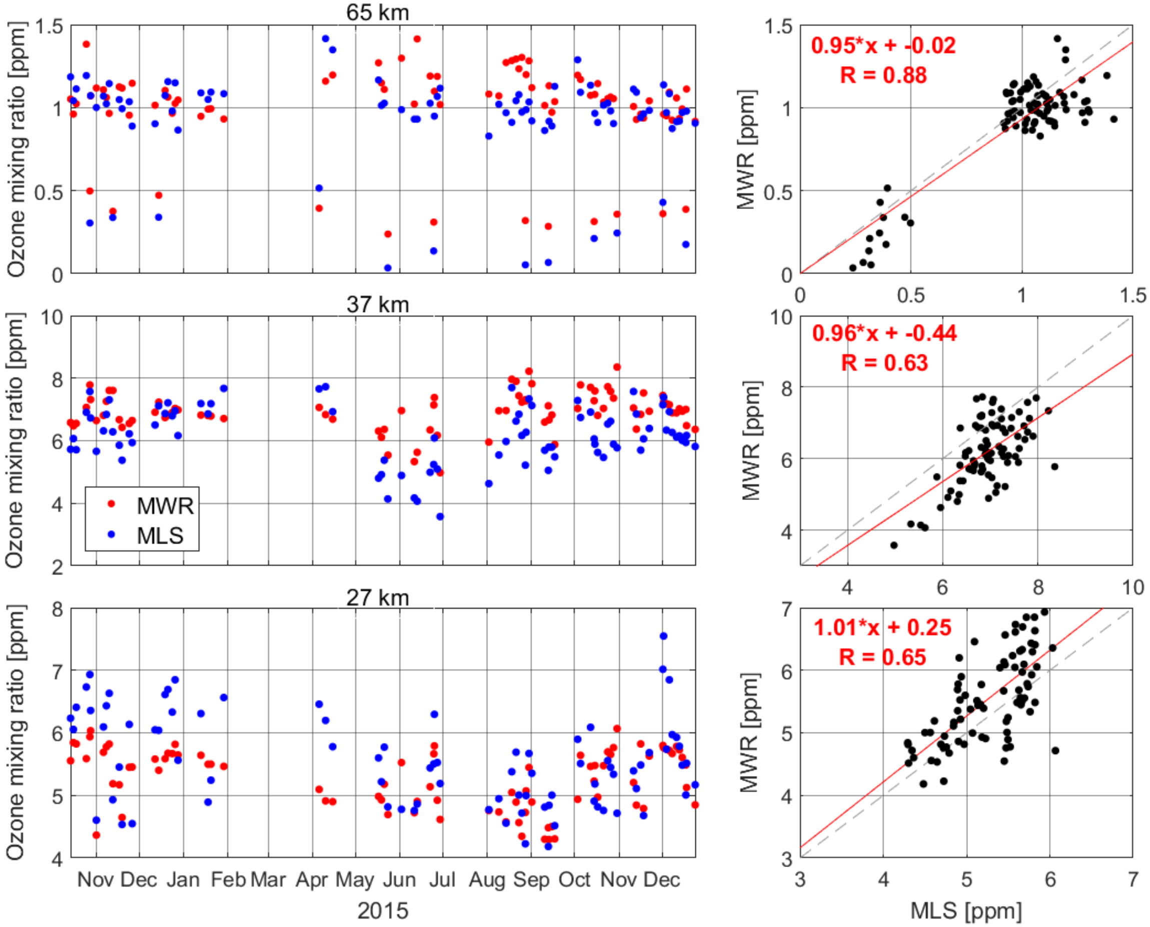


Figure 5 (left) MLS (red dots) and MWR (blue dots) ozone mixing ratio at the same time and within a box of ±0.2 in latitude and ±5º in longitude from the OAPA location for three altitudes: 27, 37, and 65 km. The analysed period covers from October 2014 to December 2015, with a total of 84 overlap measurements; (right) Scatter plot between MLS and MWR measurements for the three altitudes analysed.

	Alt.	N	Slope	Intercept *[vmr(ppm)]*	R	MBE
MWR-MLS	27 km	84	1.01	0.24	0.65	+5%
	37 km	84	0.96	-0.43	0.63	-11%
	65 km	84	0.95	0.02	0.88	-7%
MWR-DIAL	27 km	30	0.93	0.36	0.73	-1%

Table 1 Statistical parameters of the MWR respect the MLS and DIAL measurements intercomparison. N: number of intercomparison pairs; R: correlation coefficient; MBE: Mean Bias Error.

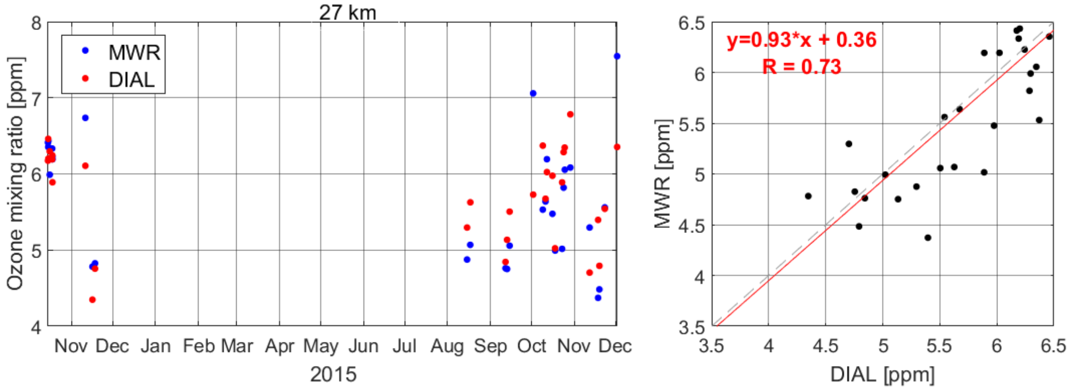


Figure 6 (left) DIAL (red dots) and MWR (blue dots) ozone mixing ratio at the same time for 27 km between October 2014 and December 2015; (right) Scatter plot between DIAL and MWR measurement.

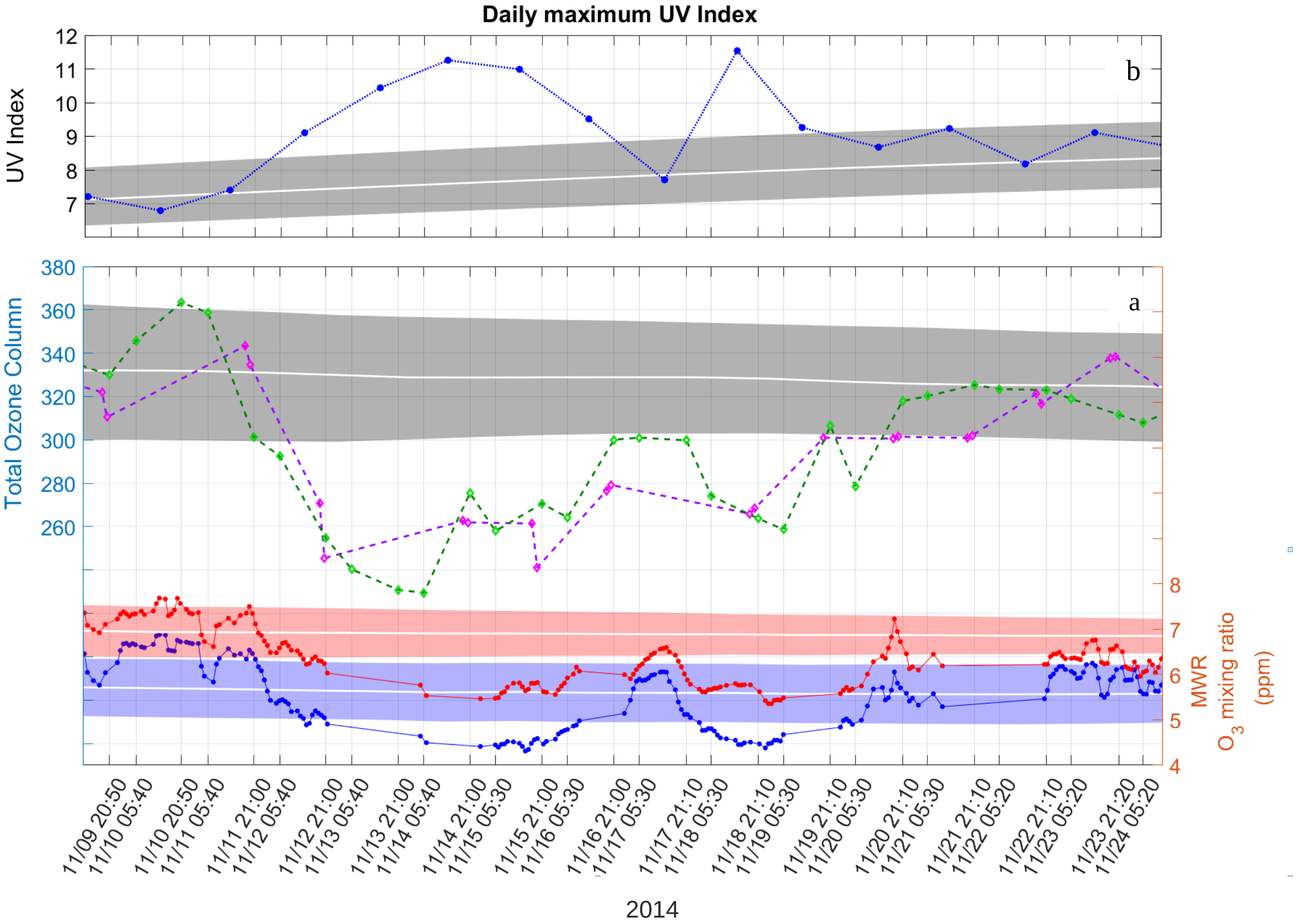
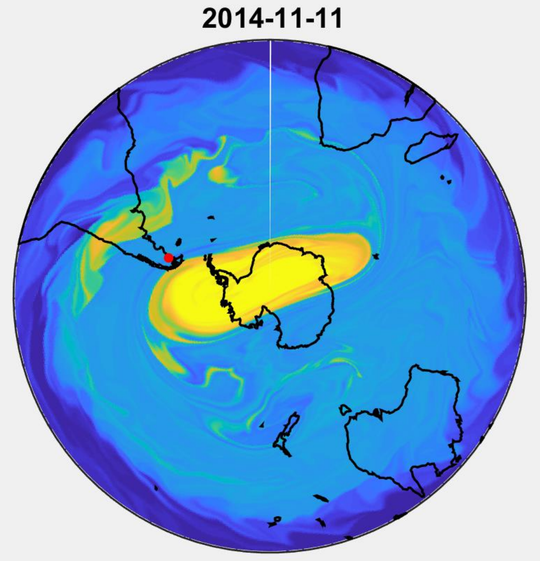
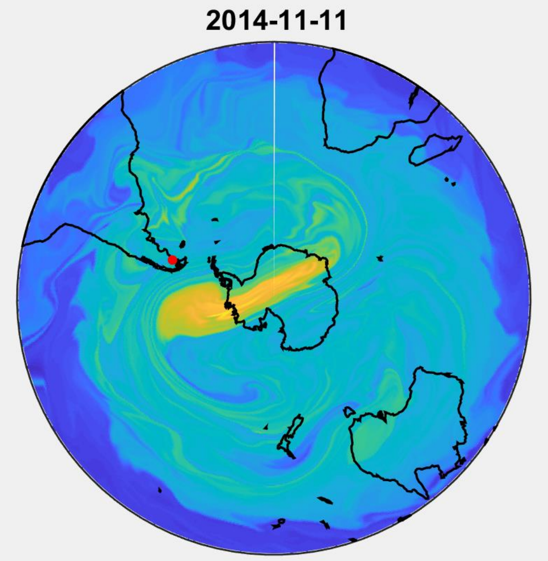
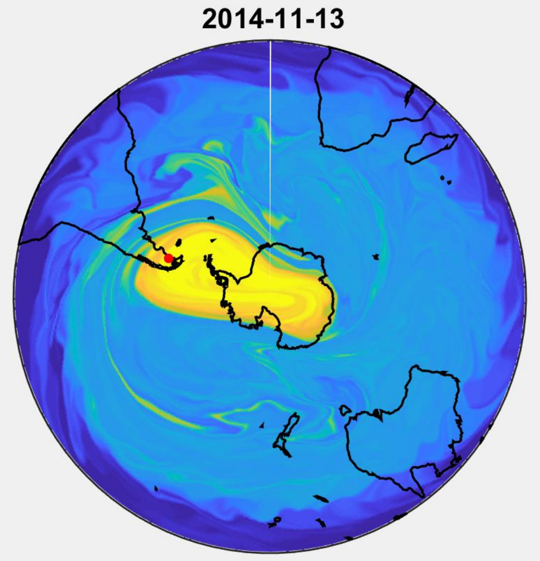
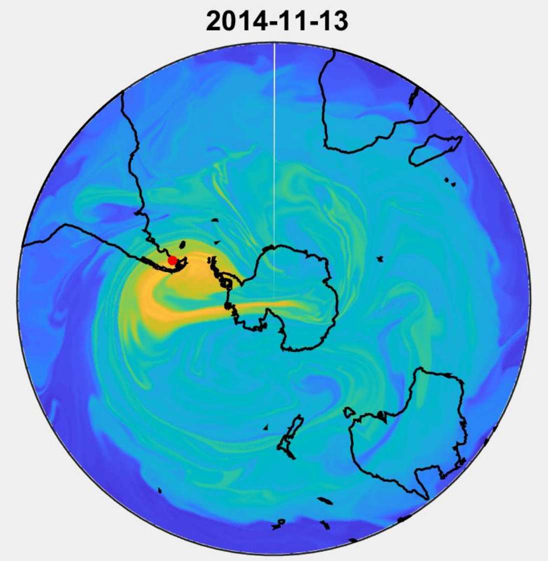
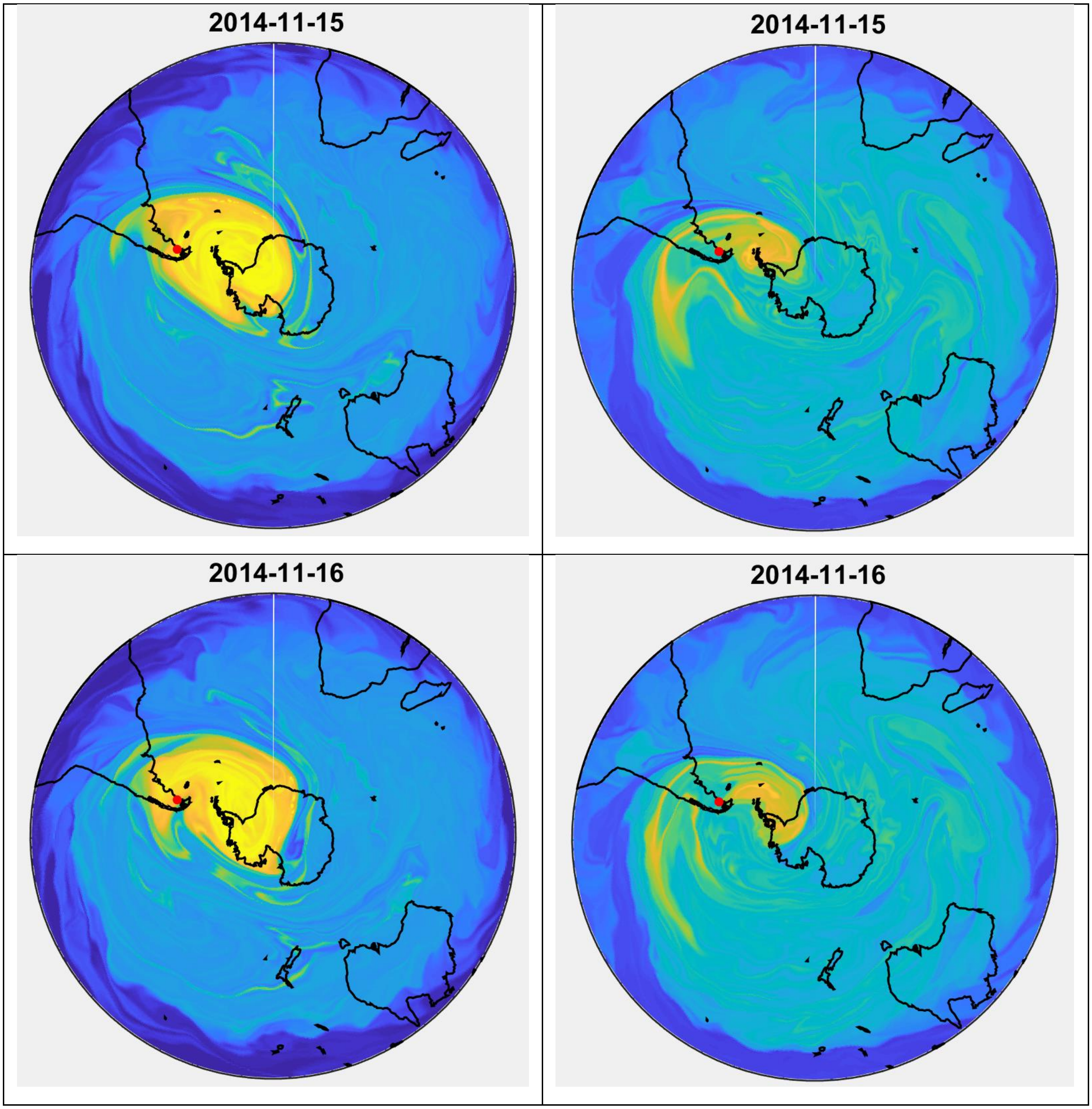


Figure 7. Atypical event of Antarctic ozone hole influence over Río Gallegos. (a) (Bottom) Time evolution of the MWR ozone mixing ratio at 27 km (red line) and 37 km (blue lines). Light red and light blue areas represent the ozone mixing ratio zonal climatology at both altitudes calculated using MLS database (2004 - 2016). (Top) Time evolution of total ozone column measured with the ground-based SAOZ instruments (green dots) and OMI (purple dots) in Dobson Units. White line and grey area represent the climatology and one SD calculated using the OMI data-base (2004 - 2017). (b) Time Evolution of the Daily maximum Ultraviolet Index measured with the ground-based solar radiometer YES UVB-1 at OAPA. White line and grey area represent the climatological UVI at noon in Río Gallegos.

675K	950K
 2014-11-11	 2014-11-11
 2014-11-13	 2014-11-13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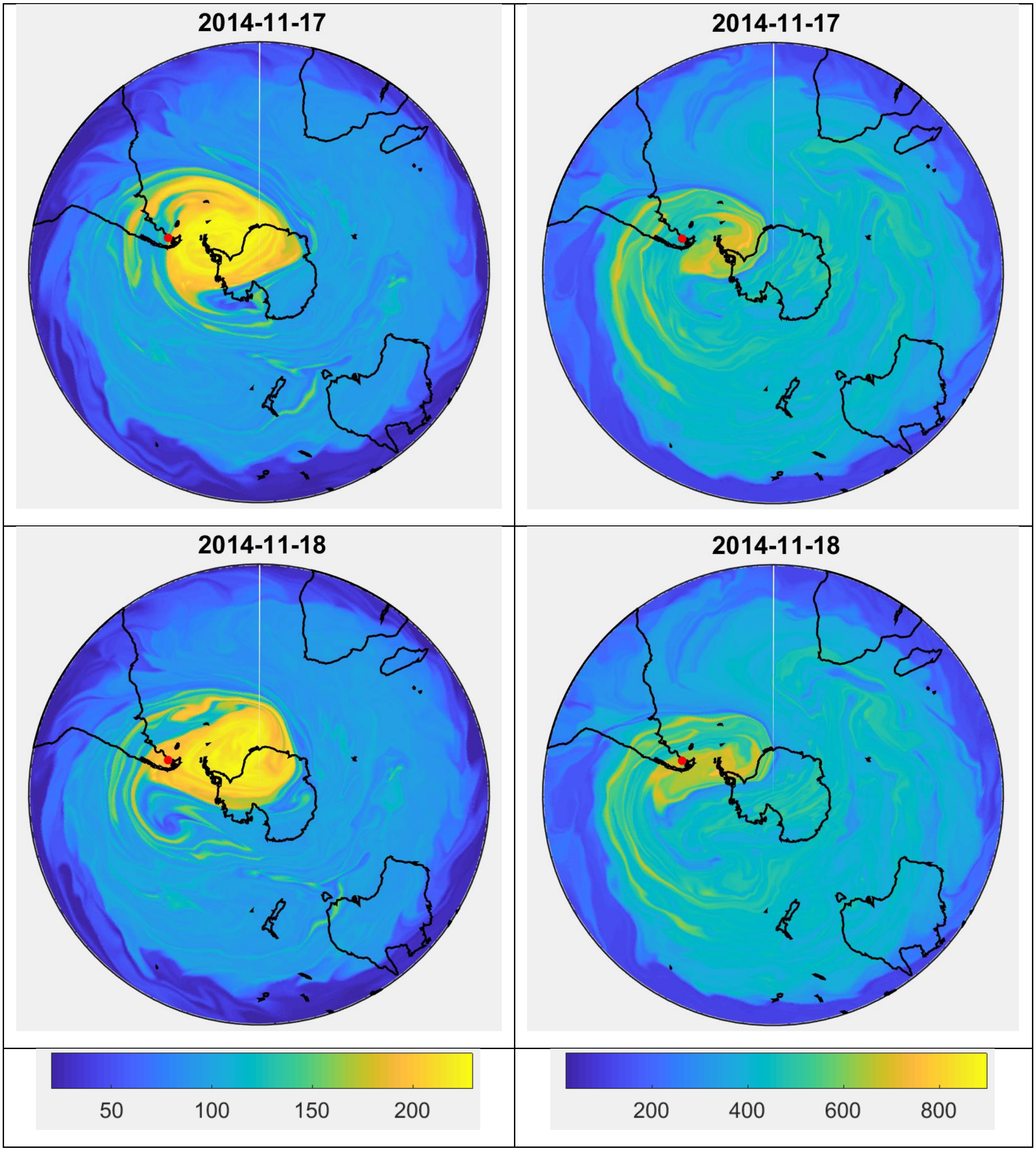

Figure 8 Advected Potential Vorticity maps assimilated with the MIMOSA model for two potential temperatures: 675K (left) and 950K (right). Maps show the evolution of the polar vortex at both potential temperatures.

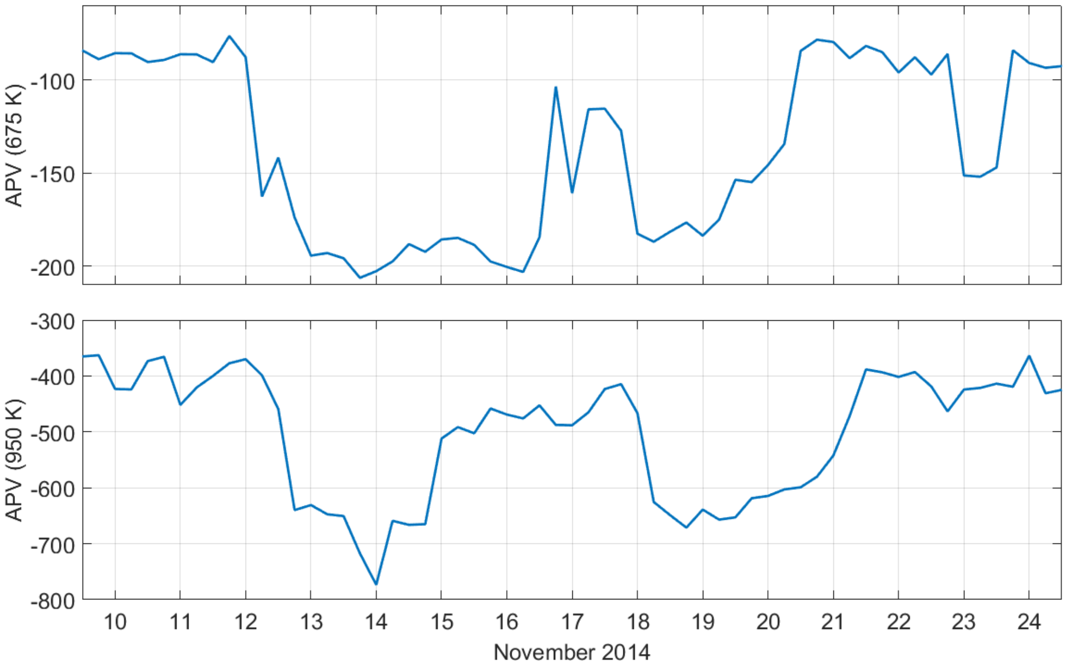

Figure 9 Time evolution of Advected Potential Vorticity assimilated with the MIMOSA model over Río Gallegos (-51.6; -69.3) at 675 K (top) and 950 K (bottom)