

## ***Interactive comment on “Analysis of an event of short term ozone variation using a Millimeter-Wave Radiometer installed in subpolar region” by Pablo Facundo Orte et al.***

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(A clearer .pdf file is upload as supplement file)

Answers to the referees comment's:

SpeciñÇ comments:

In the abstract:

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RC: The abstract must clearly highlight the most signiñÇcant scientiñÇ result, besides iñÇrst 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 Isentropie 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 scientiñÇ 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 inñÇuence the ozone content of medium- and low-latitude regions through the release of polar iñÇlaments, 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.*

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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 29 to pg. 4 line 5 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,

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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 11).

“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).”

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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 Arctic 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 16-18).

"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 tongue in literature. Referring the paragraph in the literature.

AC: This is modified as described above (pg. 3, line 19).

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).

In the 2. Materials and methods:

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

AC: The definition of "Glass Dewar" was added (pg.5, line 17).

"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 paragraph.

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

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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  $T_b$  is the brightness temperature,  $T$  is the temperature of the source, and  $\tau_a$  is the total optical thickness in the optical path of radiation propagation. In the problems of remote sensing of the atmosphere,  $T_b$  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:

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$$T_{(b_{low})} = T_{trop} (1 - e^{-\tau_z / \cos(\theta_{low})}) + T_{sys}$$

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

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

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

$$\ln(T_{hot} - T_{low}) = \ln(T_{hot}' - T_{low}) - \tau_z / \cos(\theta_{low})$$

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

Figure. Example of the retrieval of opacity from MWR observations. —o— 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 19): "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

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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 14-20.

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).

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, 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 9):

"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.,

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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 (please, see load figure 1):

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:

"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

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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

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one (MLS).

RC: The results of this section should be discussed in the literature. This is a major ĩŃaw 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 ĩŃaw 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.

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 28: 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 6: 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

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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

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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 progress 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 (51.6° S; 69.3° W) at different altitudes are reported for the first time. Río Gallegos is located in sub-polar 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".

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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>

(A more clear .pdf file is upload as supplement file)

Please also note the supplement to this comment:

<https://www.ann-geophys-discuss.net/angeo-2019-17/angeo-2019-17-AC1-supplement.pdf>

Interactive comment on Ann. Geophys. Discuss., <https://doi.org/10.5194/angeo-2019-17>, 2019.

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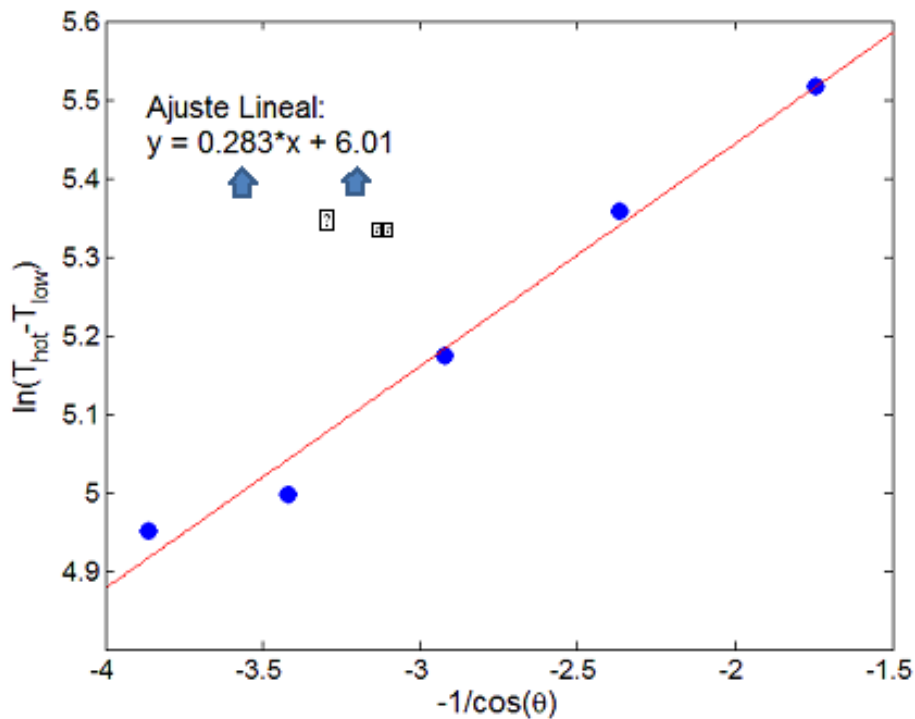


Fig. 1.

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	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%

Fig. 2.