Analysis of a spring 2013 Antarctic ozone hole pass over Río Gallegos, Argentina.

Cristian Laino Baldini
Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET)
Instituto de Hidrología de Llanuras (IHLLA)
Centro de Investigaciones en Láseres y Aplicaciones, UNIDEF (CITEDEF-CONICET)
Tandil, Argentina
cristian.laino.5@gmail.com

Pablo Orte
Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET)
Centro de Investigaciones en Láseres y Aplicaciones, UNIDEF (CITEDEF-CONICET)
Tandil, Argentina
pfacundo.orte@gmail.com

Facundo Carmona
Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) Instituto de Hidrología de Llanuras (IHLLA)
Tandil, Argentina
facundo.carmona@rec.unicen.edu.ar

Elian Wolfram
Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET)
Servicio Meteorológico Nacional (SMN) Buenos Aires, Argentina
ewolfram@gmail.com

Raúl D'Elia
Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) Centro de Investigaciones en Láseres y Aplicaciones, UNIDEF (CITEDEF-CONICET)
Buenos Aires, Argentina
raul.delia@gmail.com

Abstract—**During springtime, subpolar regions in the Southern Hemisphere are influenced by the Antarctic ozone hole (AOH), leading to variations in total ozone column (TOC) at different latitudes. This phenomenon impacts on the ultraviolet (UV) solar radiation reaching Earth's surface.**

This work focuses on a specific case study at Río Gallegos, Argentina (51.5 °S, 69.3 °W; 15 m a. s. l.), during the period from September to November 2013 when the AOH passed over the region. TOC measurements from satellite data obtained from OMI and a ground-based SAOZ instrument were analyzed, and climatological TOC was calculated.

On the specific date of October 16, 2013, a TOC value of 178.5 DU was found, while the climatology of the TOC calculated for that day was equal to 325.9 DU.

On the day of the observed TOC decrease, the UVI was measured with ground-based Multi Band Filter Radiometer GUV-541 and it was also calculated under clear sky conditions using a parametric model adapted for Río Gallegos to analyze the impact of the ozone hole on the surface UV radiation. Subsequently, the erythemal daily doses of UV radiation was retrieved. We estimate an erythemal daily dose under clear sky conditions of 5.6 kJ/m², which represents an increase greater than 100% with respect to the climatology (2.7 kJ/m²). The measurement reflected values below the climatology due the strong attenuation by clouds.

Keywords—total ozone column, ultraviolet index, OMI, SAOZ, GUV-541

I. INTRODUCTION

Ozone is a vital atmospheric trace compound, reaching its highest concentration in the stratosphere, specifically between 20 and 25 km, where it forms the "ozone layer" [1]. Its crucial role lies in absorbing harmful solar UVB radiation, safeguarding life on Earth [2; 3]. Without atmospheric ozone, life as we currently know it would not be possible. While the primary production of ozone occurs in the mesospheric-stratospheric equatorial region due to higher solar radiation levels, the maximum concentration is observed over the polar regions [2]. This zonal distribution can be attributed to the Brewer-Dobson circulation [4; 3] which transports ozone-rich air masses from the Equator to the poles and into the stratosphere.

However, since the 1970s, a significant reduction in the ozone layer has been witnessed over the Antarctic region during the austral spring seasons within the polar vortex, known as the AOH [5; 6]. This ozone depletion is a direct result of human activities releasing substances containing chlorine and bromine into the atmosphere, known as ozone-depleting substances (ODS) [7]. The consequences of ozone reduction are most prominently observed through the increased levels of harmful solar UVB radiation [8; 9].

A significant depletion of the ozone layer over Antarctica during the spring season was identified in the 1980s, [5; 6] prompting the study and ongoing monitoring of this phenomenon known as the AOH. This seasonal event is limited to specific weeks of the year, taking place in the Southern Hemisphere between August and November [10]. Ozone depletion directly affects the levels of solar UV radiation reaching the Earth's surface, resulting in significant increases in the UVI when skies are cloudless.

The global solar UVI is a measure of the intensity of solar UV radiation to induce erythema (sunburn). The index is expressed as a value above zero, the higher it is, the greater the probability of skin and eye damage, and takes less time for those injuries to produce [11].

During the austral springtime, the Antarctic polar vortex undergoes changes in its size and shape, reaching subpolar regions as a result of tropospheric-stratospheric dynamical processes. As a result, the Antarctic polar vortex can extend over the continental South American region at subpolar latitudes. This situation can lead to significant decreases in the TOC content, reaching unusual levels due to the passage of air masses with low ozone concentrations, influenced by the AOH [12; 13; 14]. The occurrence of AOH passage is identified using a TOC threshold of 220 DU. However, there may be other notable reductions in ozone concentrations above 220 DU, which are associated with the dynamics of the Antarctic polar vortex. These cases are referred to as "ozone hole influence".

Measuring the TOC has been carried out globally since the 1930s using ground-based instruments such as Dobson spectrophotometers [15]. However, it was only in the 1950s that high-quality measurements of TOC became established, primarily through the utilization of modern automated instruments like SAOZ (Systeme d'Analyse par Observation Zenithale) [16].

Despite the Montreal Protocol being in force for over 30 years, the anticipated recovery of the ozone layer at mid-latitudes is only now beginning to show signs, as the removal rate of ODSs controlled by the protocol is three to four times slower than their initial release rate [17]. Moreover, year-to-year variability in TOC makes it difficult to attribute these trends to declining ODS concentrations. Detecting significant increases in TOC outside Antarctica, therefore, requires much more time compared to detecting the previous decline [18].

The gradual closure of the Antarctic ozone hole is expected, with TOC values returning to those of 1980, shortly after the mid-century, around 2065. However, the recovery of the AOH may be influenced by future climate change scenarios. Under low climate change mitigation scenarios, updated projections from chemistry-climate models suggest that the ozone hole could recover around 2050 [18].

Because of the aforementioned factors, it is crucial to monitor ozone levels using ground-based instruments and compare them with satellite data for midlatitude regions [19; 20; 21; 22]. In the Southern Hemisphere, these regions, characterized by high population density, are strongly influenced by the AOH [6; 10, 13; 23; 24; 25; 26; 27].

Consistent and reliable results in capturing variations in TOC levels in Río Gallegos have been found in both OMI and SAOZ instruments [21]. Their studies revealed a strong correlation between the two measurements, with a correlation coefficient of 0.94 for daily average TOC. Additionally, when comparing SAOZ measurements at sunrise and sunset, the correlation coefficients were 0.88 and 0.92, respectively.

In this study, we provide an analysis of the AOH passage over Río Gallegos and its impact on TOC, surface UVI and erythemal daily doses during the spring of 2013. Our approach incorporates ground-based TOC and UV measurements, satellite retrievals, and parametrizations. By combining these methods, we analyze TOC and surface UVI measurements under cloud-free sky and actual conditions. To enhance our understanding of the impact of the AOH passage over this region, TOC and UVI climatology was also calculated.

On the one hand, daily TOC data for the year 2013 from Río Gallegos were analyzed. This data was obtained by the OMI on board National Aeronautics and Space Agency (NASA) Aura´s Satellite, along with ground-based SAOZ instrument data. OMI TOC data spanning the period from 2004 to 2023 has been used to calculate its climatology. On the other hand, global solar UVI was calculated using a Multiband Filter Radiometer (MBFR) GUV-541 (Biospherical inc.) and a parametric model. Similarly to TOC, climatological UVI was calculated using GUV-541 data. Finally, erythemal daily doses were determined from the corresponding UVI values.

II. MATERIALS AND METHODOLOGY

This study focuses on the area of Río Gallegos, Argentina (51.5 °S, 69.3 °W, 15 m a. s. l.) (Figure 1) where measurements of TOC and UVI were conducted.

TOC measurements were obtained from two sources: OMI-Aura satellite data and SAOZ ground-based observations. The SAOZ instrument belongs to Laboratoire Atmosphères, Milieux, Observations Spatiale (LATMOS/CNRS) and is operated at the Observatorio Atmosférico de la Patagonia Austral (OAPA) which is affiliated to Centro de Investigaciones en Láseres y Aplicaciones (CEILAP). The strategic location of the OAPA, in close proximity to Antarctica, provides an ideal site for investigating subpolar stratospheric ozone. On the other hand, UVI were calculated by means of a parametric model under clear sky conditions, allowing for quantification of the potential increase in surface UVI in a cloud-free scenario, while measurements from a Multi Band Filter Radiometer GUV-541 were analyzed to determine the actual impact and cloud attenuation on the UVI.

Figure 1. Río Gallegos location (taken from Google Earth).

A. Ozone measurements: OMI and SAOZ

As part of the Earth Observing System (EOS), the OMI, on board the AURA satellite, began measuring TOC in 2004 with the aim of extending the existing record from the TOMS satellite. In addition to monitoring ozone levels, OMI also retrieves atmospheric constituents such as total concentrations of NO_2, SO_2, and aerosols. This instrument utilizes a UV-VIS spectrometer to measure both reflected and backscattered solar radiation, offering a spectral resolution spanning from 0.45 to 0.63 nm in nadir view. It provides near-global coverage within a single day, with a spatial resolution ranging from 13 to 24 km [28]. For this study, TOC overpass product from OMI, known as OMDOAO3 was utilized. The dataset can be accessed and downloaded from https://avdc.gsfc.nasa.gov/index.php (last accessed in July 2013)

The SAOZ (SN 26) UV-VIS spectrometer (300–650 nm) is a ground-based instrument [14] deployed at OAPA observatory on March 11th, 2008, and is an integral part of LATMOS/CNRS. In 2009, it was incorporated into the NDACC (Network for the Detection of Atmospheric Composition).

SAOZ captures sunlight scattered from the zenith sky using the differential optical absorption spectroscopy (DOAS) method to retrieve total ozone and nitrous dioxide columns. It performs measurements of spectral diffuse solar irradiance at the zenith twice a day (at sunrise and sunset), for solar zenith angles (SZA) between 86° and 91° [29]. The TOC measurements utilize the Chappuis visible band (450– 550 nm), as ozone cross sections in this range exhibit low sensitivity to temperature variations. The installed SAOZ instrument at Río Gallegos has a spectral resolution of 0.9 nm.

To obtain vertical column densities (VCDs) from measured slant column densities (SCDs), the SAOZ retrieval procedure follows the recommendations outlined by the UV- VIS NDACC Working Group. It involves spectral window analysis, absorption cross sections, and the application of daily air mass factors. Look-up tables (LuTs) derived from the UVSPEC/DISORT radiative transfer model, using TOMS V8 ozone and temperature profiles climatology [30], are employed for the estimation of air mass factors for ozone.

A detailed description of the SAOZ measurements and their associated error analysis (~6 %) can be found in Hendrick et al. (2011). The SAOZ database was downloaded from http://saoz.obs.uvsq.fr/ (last access: July 2023).

B. UVI measurements and parametric model for Río Gallegos.

A Multi Band Filter Radiometer GUV-541(SN 29242) was employed in order to obtain ground-based UVI (UVIg) measurements. The GUV-541 features five UV measurement channels, each with central wavelengths at 305, 313, 320, 340, and 380 nm, and an approximate bandwidth of FWHM=10 nm. This instrument is a component of the passive sensing station OAPA in Río Gallegos, Santa Cruz, Argentina.

To calculate the UVI under cloud-free, unpolluted, low surface albedo (UVIp) conditions, the following equation was utilized:

$$UVI \sim 13.13\, \mu^{2.69} \left(\frac{TOC}{300}\right)^{-1.23} \qquad (1)$$

where μ is the cosine of the SZA and TOC is the total vertical ozone column (in Dobson Units, DU) [31]. According to Madronich, S. (2007), the error for the parametric model is up to 10%. The coefficients of equation 1, were those obtained for Río Gallegos by means of a non-linear fitting with calibrated UVI measurement [32]. Orte, P. F. (2017) investigation suggests a relative difference between the adjusted parametric model and measurement of the GUV-541 close to 10%.

C. Case Study

Observing the dataset from OMI, an atypical case of AOH over Río Gallegos stands out on October 16th, 2013, when the TOC value found was below a threshold of 220 DU, used to identify the passage of the AOH. Given this scenario, OMI and SAOZ data were analyzed through September to December of 2013, since in austral spring times the AOH is when its size and shape changes. The climatology of TOC was derived from the 2004-2023 OMI database by computing daily averages across all years. Additionally, we calculated a moving mean with a 30-day window (15 days before and 15 days after). As a result, we obtained both a moving mean and a moving standard deviation of 1 SD.

UVIg obtained by the GUV-541 was compared with calculated UVIp for the September - November period. Replacing TOC measurements with climatology O3 in Equation 1, climatology UVI (UVIc) is obtained.

To determine the erythemal daily dose of UV radiation on October 16, 2013, UVIp and UVIg curves were integrated over time. By calculating the area beneath each curve, a quantitative measure of UV erythemal daily dose was obtained. It is important to note that UVIg measurements were available between 11 AM and 9 PM (UTC), hence, the integration of UVIg and UVIp were calculated for this period of time.

III. RESULTS

Figure 2 (top) shows the time evolution of TOC measurements from OMI (light blue line) and SAOZ (black dots) for OAPA from September to November 2013. The white line and gray area represent the climatology and 1 SD, both calculated from the OMI database (2004-2023). The dotted line at TOC=220 DU represents the threshold that identifies the passage of the AOH. Figure 3 shows the distribution of TOC across the Southern Hemisphere on October 16, 2013. In this visualization, regions with minimal ozone content are represented by shades of purple and blue, whereas areas with higher ozone concentrations are depicted by hues of yellow and red. The passing of the AOH over Río Gallegos is observed, leading to low TOC values, in correspondence with OMI and SAOZ measurements. As a consequence of this event, the TOC dropped significantly to 178.5 DU, the second lowest recorded value by OMI since 2005 (173.19 DU). In contrast to the daily moving mean, which is 325.9 DU, the 2013 AOH passage showed a 45.2% reduction. In addition, OMI´s TOC measurement resulted in 37.8% times smaller than 1 SD climatology for that day, and even 18.9% times smaller than the AOH threshold.

For the same period, UVIp was also calculated. Figure 2 (bottom) presents the UVIp for the period September to November calculated from the parametric model using OMI TOC as input (blue line). The colored dots depict the daily maximum UVIp (i.e., minimum SZA) following the color palette proposed by Luccini et al., 2023. It is notable that most UVIp values are close to the mean or within one standard deviation of the climatology. However, a UVI value of 11, attributed to low TOC on October 16th, 2013, stands apart.

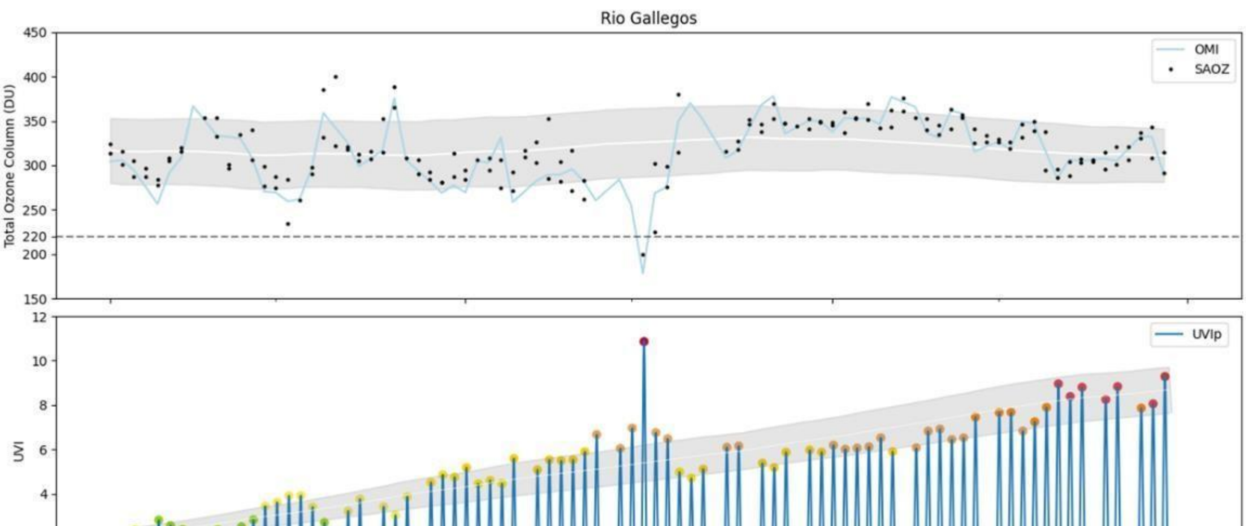

Figure 2. Event of AOH passing over Río Gallegos during the period September to December 2013. Top figure indicates TOC measurements from OMI (light blue line) and SAOZ (black dots). Bottom figure indicates modeled UVI for cloudless sky conditions. Colored dots correspond to the maximum UVI recorded for each day of measurement [33]. In both cases, gray area and white line represent the climatology and 1 standard deviation, utilizing the OMI database (2004-2023).

ISBN: 978-950-766-230-0

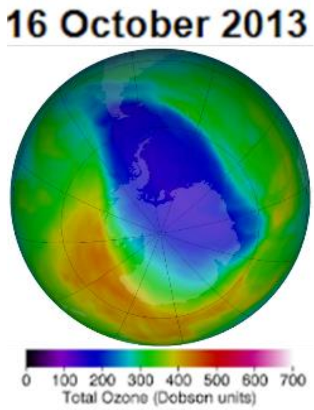

Figure 3. NASA´s Ozone Watch false-color visualization of the TOC distribution over the Southern Hemisphere on October 16, 2013.

When examining Figure 4, which displays UVIp, UVIc, and UVIg for that particular day, lower values of UVIg, measured by the GUV-541, than UVIp is observed. This difference, due to cloud attenuation, results in a low to moderate UVI risk level at surface, even below UVIc. More specifically, on that date, UVIp peaked at 10.9 at 16:23:00 UTC, UVIg reached 4.4 at 18:04:00 UTC, while UVIc's maximum value was 5.2 at 16:23:00 UTC.

Cloudiness acts over UV and VIS solar radiation, influencing strongly over atmospheric radiative balance. With the objective of quantifying the impact of the low ozone case and the blockage caused by clouds on October 16, 2013, the UV erythemal daily dose from UVIp, UVIc and UVIg were calculated and compared.

Under free cloud conditions, the predicted dose resulted in 5.6 kJ/m2, while climatologic UV erythemal daily dose is 2.7 kJ/m^2. As a result, if the sky were cloud-free, the predicted dose doubles the climatology. However, the measured erythemal daily dose resulted in 1.8 kJ/m2, showing that climatology UVI exceeds the measured by 50%. Finally, the comparison between clear sky condition and the measurements reflects a 201.1%, which represents the attenuation by the clouds of the increase in the UV that the low ozone case study would have produced on the surface.

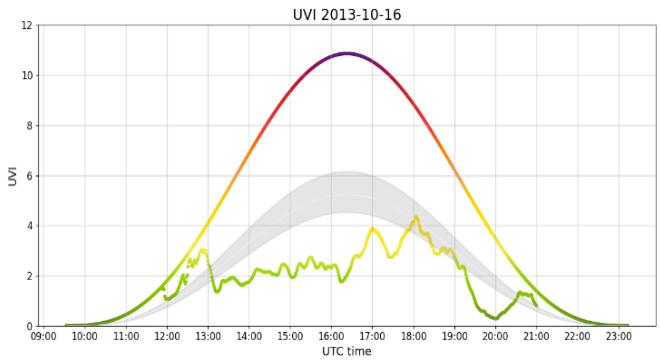

Figure 4. UVI for October 16th of 2013. UVIp (bell shaped) and UVIg are colored according to UVI color palette [33]. UVIc and 1 SD are indicated with white line and gray shade, respectively.

IV. CONCLUSIONS

Throughout the study period from September to November 2013, we identified a notably low TOC value in NASA's OMI database for Río Gallegos on October 16, 2013. The observation aligns with the NASA´s Ozone Watch TOC distribution visual representation, as it shows the AOH passing over the study site. To analyze this event, we combined ground measurements from SAOZ and the GUV-541, satellite retrievals from NASA's OMI, and parametrizations. Thus, TOC and UVI climatology was calculated, as TOC levels and UVI at the surface under diverse conditions were measured, next, erythemal daily doses were calculated.

The low TOC value recorded by OMI on October 16th of 2013 was equal to 178.5 DU, representing a drastic decrease compared to the daily moving mean of 325.9 DU, indicating a 45.2% reduction. Furthermore, OMI's TOC value is 37.8% lower than the 1 SD climatology for that day and even 18.9% smaller than the designated threshold.

UVI values were calculated for the same period of time using the parametric model, with OMI TOC as input. Most UVI values were found to be close to the mean or within one standard deviation of the climatology. However, a UVI value of 11 was recorded on October 16th, attributed to the low TOC levels.

Examining the results of UVIg and UVIp for October 16th, a significant difference was observed. The UVIg measurement from the GUV-541 instrument was lower than the predicted UVIp value due to the cloudiness. This resulted in a low to moderate level of UV radiation risk at the surface, even below UVIc.

On the other hand, a quantitative analysis of UV radiation erythemal daily dose and cloud- induced attenuation was conducted for October 16th, 2013. The results revealed erythemal daily dose levels of 5.6 kJ/m^2, 2.7 kJ/m^2 and 1.8 kJ/m^2, from predicted, climatological and ground measurements, respectively. These findings indicate that the predicted UV radiation erythemal daily dose for that day exceeded the climatology by 107.4%, however, the presence of clouds led to a significant attenuation of 201.1%, and a 50% difference between climatology and ground -based measurement.

ACKNOWLEDGMENT

The authors would like to thank LATMOS/CNRS and NASA for the availability of the data from SAOZ and OMI, respectively.

REFERENCES

[1] *London, J.: The observed distribution of atmospheric ozone and its variations, ozone in the free atmosphere, edited by: Whitten, R. C. and Prasad, S. S., New York, Van Nostrand Reinhold, chap. 1, 11–80, 1985.*

[2] *Salby, M. L.: Fund, Atmos. Phys. International geophysics series, Academic Press, 61, 29–54, 1996.*

[3] *Dobson, G. M. B.: Origin and distribution of polyatomic molecules in the atmosphere, Proc. R. Soc. A,236, 187–193, 1956.*

[4] *Brewer, A. W.: Evidence for a world circulation provided by the measurements of helium and water vapor distribution in the stratosphere, Q. J. Roy. Meteor. Soc., 75, 351–363, 1949.*

[5] *Chubachi, S. (1984) Preliminary result of ozone observations at Syowa Station from February, 1982 to January, 1983. Memoirs of National Institute of Polar Research (Japan). Special Issue, 34, 13–20.*

[6] *Farman, J.C., Gardiner, B.G. & Shanklin, J.D. (1985) Large losses of total ozone in Antarctica reveal seasonal ClOx/NOx interaction. Nature, 315, 207–210.*

[7] *World Meteorological Organization (WMO): Scientific Assessment of Ozone Depletion: 2010, Global Ozone Research and Monitoring Project-Report No. 52, Geneva, Switzerland, 2011a.*

[8] *Casiccia, C., Zamorano, F. & Hernandez, A. (2008) Erythemal irradiance at the Magellan's region and Antarctic ozone hole 1999–2005. Atmosfera, 21(1), 1–12.*

[9] *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., Quel, E.J. 2012. 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. doi.org/10.5194/angeo-30-1435-2012.

[10] *Solomon, S. (1999) Stratospheric ozone depletion: a review of concepts and history. Reviews of Geophysics, 37(3), 275–316.*

[11] *World Health Organization, WHO (2002) Global Solar UV Index, Publication WHO/ SDE/ OEH/ 02.2. World Health Organization, Geneva, Switzerland, pp. 1–28.*

[12] *Wolfram, A. E., Salvador, J., D'Elia, R., Casiccia, C., Leme, N. P., Pazmiño, A., Porteneuve, J., Godin-Beekman, S., Nakane, H., and Quel, E. J.: New Differential absorption lidar for stratospheric ozone monitoring in Patagonia, south Argentina, J. Opt. A, 10, 589–595, 2008.*

[13] *Orte, P.F., Salvador, J., Wolfram, E., D'Elia, R., Nagahama, T., Kojima, Y., Tanada, R., Kuwahara, T., Morihira, A., Quel, E., Mizuno, A. 2011. Millimeter wave radiometer installation in Río Gallegos, southern Argentina, Int. Conf. on Applications of Opt. and Photonics, edited by: Costa, M.F.M., Vol. 8001, Proceedings of SPIE, doi.org/10.1117/12.894578.*

[14] *Orte, P. F., Wolfram, E., Salvador, J., Mizuno, A., Bègue, N., Bencherif, H., Bali, J. L., D'Elia, R., Pazmiño, A., Godin-Beekmann, S., Ohyama, H., and Quiroga, J.: Analysis of a southern sub-polar short-term ozone variation event using a millimeter-wave radiometer, Ann. Geophys., 37, 613–629, https://doi.org/10.5194/angeo-37-613-2019, 2019.*

[15] *Dobson, G. M. B.: Forty years' research on atmospheric ozone at Oxford: A history, Appl. Optics, 7, 387–405, 1968.*

[16] *Pommereau, J. P. and Goutail, F.: O3 and NO2 ground-based measurements by visible spectrometry during Arctic winter and spring 1988, Geophys. Res. Lett., 15, 891–894, https://doi.org/10.1029/gl015i008p00891, 1998.*

[17] *Steinbrecht, W., Hegglin, M. I., Harris, N., & Weber, M. (2018). Is global ozone recovering? Comptes Rendus Geoscience, 350(7), 368–375. doi.org/10.1016/j.crte.2018.07.012.*

[18] *WMO. (2022). Scientific Assessment of Ozone Depletion: 2022, GAW Report No. 278. World Meteorological Organization, Geneva, Switzerland.*

[19] *Balis, D., Kroon, M., Koukouli, M.E., Brinksma, E.J., Labow, G., Veefkind, J.P., McPeters, R.D. 2007. Validation of Ozone Monitoring Instrument total ozone column measurements using Brewer and Dobson spectrophotometer ground-based observations, J. Geophys. Res., 112, D24S46, doi.org/10.1029/2007JD008796.*

[20] *McPeters, R., Kroon, M., Labow, G., Brinksma, E., Balis, D., Petropavlovskikh, I., Veefkind, J.P., Bhartia, P.K., Levelt, P.F. 2008. Validation of the Aura Ozone Monitoring Instrument total column ozone product, J. Geophys. Res., 113, D15S14, doi.org/10.1029/2007JD008802.*

[21] *Keckhut, P., Hauchecorne, A., Blanot, L., Hocke, K., Godin-Beekmann, S., Bertaux, J.-L., Barrot, G., Kyrölä, E., van Gijsel, J. A. E., and Pazmino, A.: Mid-latitude ozone monitoring with the GOMOS-ENVISAT experiment version 5: the noise issue, Atmos. Chem.*

[22] *Orte, F., Luccini, E., Wolfram, E., Nollas, F., Pallotta, J., D'Elia, R., Carbajal, G., Mbatha, N., Hlongwane, N. Comparison of OMI-DOAS total ozone column with ground-based measurements in Argentina. Revista de teledetección. Asociación Española de Teledetección. 2020. doi.org/10.4995/raet.2020.13673.*

[23] *Kirchhoff, V. W. J. H., Schuch, N. J., Pinheiro, D. K., and Harris, J. M.: Evidence for an ozone hole perturbation at 30_ south, Atmos. Environ., 33, 1481–1488, 1996.*

[24] *Perez, A., de Carcer, I. A., Tocho, J. O., Crino, E., Sandoval, H. F. R., Berni, M. E., Da Silva, L., Henriques, D., Cusso, F., and Jaque, F.: The extent of the ozone hole over South America during the spring of 1993, 1994, and 1995, J. Phys. D Appl. Phys., 31, 812–819, 1998.*

[25] *De Laat, A. T. J., Van Der A, R. J., Allaart, M. A. F., VanWeele, M., Benitez, G. C., Casiccia, C., Leme, N. M. P., Quel, E., Salvador, J., and Wolfram, E.: Extreme sunbathing: Three weeks of small total O-3 columns and high UV radiation over the southern tip of South America during the 2009 Antarctic O-3 hole season, Geophys. Res. Lett., 37, L14805, doi:10.1029/2010GL043699, 2010.*

[26] *Pinheiro, D. K., Peres, L. V., Crespo, N. M., Schuch, N. J., and Leme, N. M. P.: Influence of the Antarctic ozone hole over South of Brazil in 2010 and 2011, Annual Active Report 2011– National Institute of Science and Technology Antarctic Environmental Research, 1, 34–38, doi:10.4322/apa.2014.058, 2012.*

[27] *Schuch, P. A., Santos, M. B., Lipinski, V. M., Peres, L. V, Santos C. P., Cechin S. Z., Schuch, N. J., Pinheiro, D. K., and Loreto, E. L. S.: Identification of influential events concerning the Antarctic ozone hole over southern Brazil and the biological effects induced by UVB and UVA radiation in an endemic treefrog species, Ecotox. Environ. Safe., 118, 190–198, doi:10.1016/j.ecoenv.2015.04.029, 2015.*

[28] *Levelt, P.F (2006). The Ozone Monitoring Instrument. IEEE. Transactions on Geoscience and Remote Sensing, 44, 5, 1093-1101.*

[29] *Pazmiño A. 2010. O3 and NO2 vertical columns using SAOZ UV-Visible spectrometer. EPJ Web of Conferences, EDP Sciences, 2010, 9, pp.201-214. doi.org/10.1051/epjconf/201009016.*

[30] *Hendrick, F., Pommereau, J.P., Goutail, F., Evans, R.D., Ionov, D., Pazmino, A., Kyrö, E., Held, G., Eriksen, P., Dorokhov, V., Gil, M., Van Roozendael, M. 2011. NDACC/SAOZ UV-visible total ozone measurements: improved retrieval and comparison with correlative ground-based and satellite observations, Atmos. Chem. Phys., 11, 5975-5995, doi.org/10.5194/acp11-5975-2011.*

[31] *Madronich, S. (2007). Analytic Formula for the Clear-sky UV Index. Photochemistry and Photobiology, 83, 1537-1538.*

[32] *Orte, P.F., Wolfram, E., Salvador, J., D'Elia, R., Quiroga, J., Quel, E., Akira Mizuno, A. Attenuation by Clouds of UV Radiation for LowStratospheric Ozone Conditions AIP Conference Proceedings 1810, 110009 (2017); doi: 10.1063/1.4975571.*

[33] *E. Luccini, F. Orte, J. Lell, F. Nollas, G. Carbajal, E. Wolfram (2023), The UV Index color palette revisited, Journal of Photochemistry and Photobiology, 15, 100180, https://doi.org/10.1016/j.jpap.2023.100180*