GEOPHYSICAL RESEARCH LETTERS, VOL. 37, L14805, doi:10.1029/2010GL043699, 2010

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

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Received 21 April 2010; revised 1 June 2010; accepted 14 June 2010; published 27 July 2010.

[1] This paper presents an analysis of satellite and ground-based measurements of total O_3 columns and the UV index of a unique event during the 2009 Antarctic O_3 hole season. From 11 to 30 November 2009 the Antarctic vortex was located just south of the southern tip of South America rather than at its climatological position over Antarctica. Analysis of 30 years of assimilated total O_3 column and UV index measurements shows that this 20-day event was unique in the history of the ozone hole for these latitudes. During this period, small total O_3 columns and large UV index values were observed over the southern tip of South America. Comparison of ground-based and satellite measurements of total O_3 columns and satellite based calculations of the UVI index – never designed nor validated for such extreme Southern Hemisphere conditions – show excellent agreement. **Citation:** de Laat, A. T. J., R. J. van der A, M. A. F. Allaart, M. van Weele, G. C. Benitez, C. Casiccia, N. M. Paes Leme, E. Quel, J. Salvador, and E. Wolfram (2010), 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.

1. Introduction

[2] The Antarctic ozone (O_3) hole is a poster child of man's impact on climate. The main concern is the impact of the reduced thickness of the ozone layer on incoming ultraviolet (UV) radiation, which can be harmful for humans, plants and animals. A widely used metric for monitoring surface UV radiation is the UV index (UVI), which was developed under the guidance of the World Meteorological Organization [*World Meteorological Organization* (*WMO*), 1995]. The UVI integrates UV irradiances between 280 and 400 nm and takes the sensitivity of the Caucasian skin for UV radiation into account. The Tropospheric Emissions Monitoring Internet Service (TEMIS; http://www.temis.nl) provides global daily analyses and short-term predictions of the UVI based on assimilation of satellite total O_3 columns observations.

[3] During the Antarctic 2009 O_3 hole season, the Antarctic vortex became stagnant over the southern tip of South America during three weeks in November 2009. This led to continuous small total O_3 columns over the southern tip of South America and large UVI values. The empirical model for calculating the TEMIS clear sky UVI using satellite total O_3 column measurements has been tuned to ground-based measurements of UV spectra and total O_3 column measurements in De Bilt, The Netherlands and Paramaribo, Suriname [*Allaart et al.*, 2004] (see Table 1) and was never designed for extreme Antarctic O_3 hole conditions of reduced O_3 and elevated UV surface radiation levels. Total O_3 columns of 220 DU or less in combination with larger solar zenith angles occur neither at De Bilt nor at Paramaribo, hence it is a valid question how well the UVI performs for small total O_3 column conditions. This question will be addressed in this paper by using UV and O_3 observations for the unusual November 2009 episode from three ground stations situated around the southern tip of South America. Furthermore, a new 30-year satellite total O_3 column assimilation dataset [*van der A et al.*, 2010] allows analyzing this period with regard to the frequency of occurrence of total O_3 columns and UVI values and how unusual this episode was throughout the existence of the Antarctic ozone hole.

2. Observations

[4] For the validation of the satellite-based UVI calculations we use measurements from three ground stations in the southern tip of South America: Punta Arenas, Chile; Río Gallegos, Argentina; and Ushuaia, Argentina (see Table 1). All stations altitudes are close to sea level. Río Gallegos total O_3 columns and UV irradiances are measured by a Brewer IVe instrument and a GUV 541 multi-channel moderate bandwidth radiometer from Biospherical Inc, respectively. Ushuaia is employed with a Dobson spectrophotometer and a UV-B Biometer Model 501 Radiometer. Punta Arenas is employed with a Brewer MK III. The UVI is calculated from the spectral measurements, and the maximum index value is provided on a daily basis if sufficient cloud free conditions occur.

[5] The clear-sky solar noon UVI calculation uses assimilated satellite measurements of the total O_3 column, solar zenith angle and earth-sun distance [*Allaart et al.*, 2004]. The total O_3 columns used for 2009 are derived from satellite observations of total O_3 columns from SCIAMACHY

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0094-8276/10/2010GL043699

Table 1. Coordinates and Instruments of Ground-Based Measurement Stations

	Longitude	Latitude	O_3 Instrument	UV Instrument
De Bilt	5.18° E	52.10° N	Brewer MK III	Brewer MK III
Paramaribo	55.17° W	5.82° N	Brewer MK III	Brewer MK III
Río Gallegos	69.32° W	51.60° S	Brewer MK IVe	GUV 541
Punta Arenas	70.90° W	53.00° S	Brewer MK III	Brewer MK III
Ushuaia	68.31° W	54.85° S	Dobson	UV-B Biometer 501

(Scanning Imaging Absorption spectrometer for Atmospheric Cartography [*Bovensmann et al.*, 1999]) that are assimilated in the chemistry transport model TM3 to provide an analysis of global O_3 and UVI [*Eskes et al.*, 2003] as well as 9-day forecasts (not studied in this paper). The SCIAMACHY total O_3 columns are retrieved using the TOSOMI algorithm [*Eskes et al.*, 2005]. These measurements are corrected for instrument drift [*van der A et al.*, 2010].

[6] In addition, we use daily total O_3 columns obtained from the Multi Sensor Reanalysis project (MSR), which produced a 30-year total O_3 column assimilation dataset for 1979–2008 based on a total of eleven satellite instruments measuring total O_3 columns – including SCIAMACHY - that were operating during various periods within these 30 years [*van der A et al.*, 2010]. The MSR was also used for calculating clear sky UVI values for the period 1979–2008 using the same method as described above. Online sources of the various O_3 and UVI datasets used in this study are summarized in Daily MSR total O_3 columns at 12:00 UTC, http://www.temis.nl/protocols/o3field/o3field_msr.php; daily MSR maximum UVI data, http://www.temis.nl/uvradiation/MSR/uvief.php; daily SCIAMACHY assimilated total O_3 column data at 12:00 UTC for 2009, http://www.temis.nl/protocols/o3field/o3field.php; daily maximum UVI data for 2009, http://www.temis.nl/uvradiation/SCIA/uvief.php; SCIAMACHY assimilated 6-hourly total O_3 column station overpass data for 2009, http://www.temis.nl/protocols/o3field/overpass_scia.html; overpass UVI data for 2009, http://www.temis.nl/uvradiation/SCIA/stations_uv.html. Ground based measurements for local noon for the three ground stations were directly provided by the ground-station operators.

3. The 2009 Antarctic Ozone Hole

[7] Figure 1 shows the average SCIAMACHY assimilated total O_3 columns around the southern tip of South America for three periods: 1 October – 10 November, 11 – 30 November and 1–31 December, which we refer to as periods 1, 2 and 3. The left column shows the 1979–2008 climatology for these three periods using MSR results. The middle panels show the corresponding 2009 SCIAMACHY assimilated O_3 columns, and the right panels show the differences between 2009 and the MSR 1979–2008 total O_3 column climatology. The period 1979–2008 was chosen for the climatology because from 1989 onwards the large O_3 holes occurred and O_3 depletion was more or less constant [*WMO*, 2007].

[8] During Period 1, both the size and location of the 2009 O_3 hole are very similar to that of the 1979–2008 MSR climatology, with about 10% more O_3 in the rim around the Antarctic vortex. However, for Period 2 the position and extent of the hole deviates from the climatology. The vortex shifts to the Antarctic Peninsula and the edge of the O_3 hole extends over the southern tip of South America. This results in a large negative total O_3 column anomaly between the Antarctic Peninsula and South America, and a large positive anomaly at the opposite side of the vortex. During Period 3 the situation returns to normal as the vortex disintegrates and vanishes – typical for December - and the total O_3 columns return to normal values. Figure 2 shows the UVI values and anomalies corresponding to the total O_3 columns in Figure 1. The UVI anomalies show that UVI values during Period 2 are extremely large over the southern tip of South America, corresponding to the negative total O_3 column anomaly. During Periods 1 and 3 UVI values are close to the climatological values and anomalies are small.

[9] Figure 3 shows the time series of mean daily O_3 column densities and UVI values for an area over the southern tip of South America - indicated in Figures 1 and 2 - as well as the standard deviation and minimum and maximum O_3 and UVI values within this area. For all September to December days in the period 1979–2008 the combined probability distribution of MSR total O_3 columns along all longitudes was calculated for the latitudes of the area in Figures 2 and 3. The 66%, 95%, 99% and minimum/maximum total O_3 column occurrence intervals are depicted by the shaded gray areas in Figure 3.

[10] The large decrease in O_3 columns and large increase in UVI around the 10th of November 2009 are easily identified. The probability distribution shows that for Period 2 total O_3 columns are unusually small and the UVI values unusually large for these latitudes (close to or outside the 95% occurrence interval). Near the end of Period 2 the vortex quickly disintegrates while staying stagnant. At the beginning of Period 3 the situation has returned to normal.

[11] Analysis of MSR data reveals that a 20-day period with total O_3 columns outside the 95% occurrence interval and UVI values larger than 10 for up to 18 days never occurred for the period 1979–2009 at any longitude for latitudes between 52°S and 56°S during the latter two decades of November. The closest match was a 20-day period in November 1997 for a much smaller area over the South Atlantic around South Georgia (56.9°S, 32.4°W) when up to 14 days fell outside the 95% occurrence interval and up to 13 days had UVI values larger than 10. However, this period in 1997 consisted of two parts, separated by several days when total O_3 columns and UVI returned to normal values, which in 2009 clearly did not occur. No other 20-day period in November with even more than 10 days of total O_3 columns outside the 95% occurrence interval and UVI values larger than 10 occurred during 1979–2008

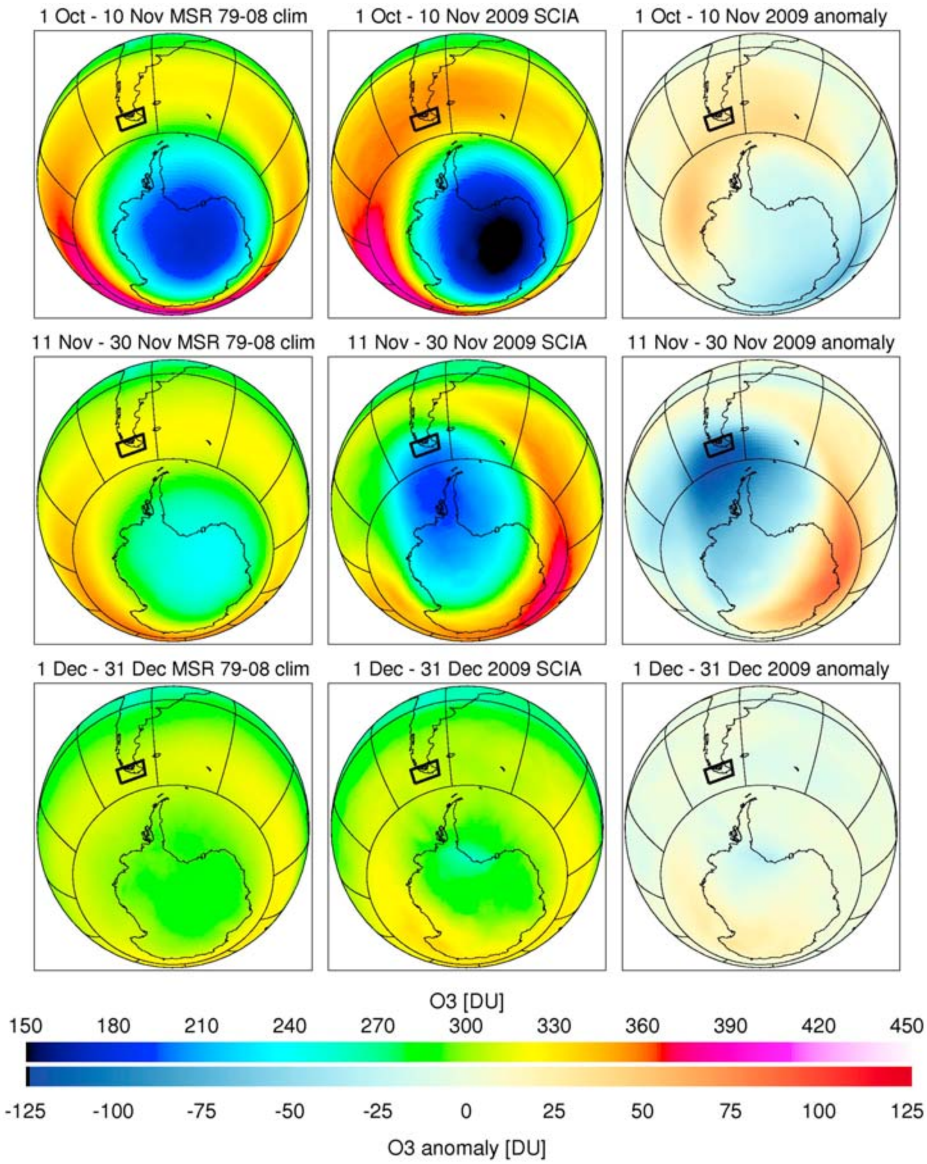

Figure 1. Average total O_3 columns for the periods (top) 1 October – 10 November, (middle) 11–30 November and (bottom) 1–31 December for the (left) 1979–2008 MSR total O_3 column climatology, (middle) the assimilated SCIAMACHY total O_3 columns for 2009 and (right) the 2009 total O_3 column anomaly with respect to the MSR total O_3 column climatology. Total O_3 column values and anomalies are in Dobson Units (~2.69 10^{16} molecules/cm^2). The box area around the most southern tip of South America represents the area used for Figure 3.

between 52°S and 56°S. The occurrence of this episode over land and populated regions makes it even more relevant.

[12] Figure 3 shows that at latitudes between 52°S and 56°S the UVI gradually increases during spring from September to the end of December. The small O_3 columns occurred late in the O_3 hole season, hence solar radiation is already quite strong, resulting in large UVI values. Persistent large UVI values of 10 or more during 20 consecutive days normally only occur equatorward of 40° latitude. The large UVI values occurred over populated regions, resulting in prolonged increased UV exposure for humans, plants and animals.

[13] Note that already at the end of September and beginning of October the edge of the Antarctic vortex passed over this region twice, which resulted in small O_3 columns and enhanced UVI values. However, because of the much larger solar zenith angles and thereby longer photon path lengths the UVI values were reduced. Nevertheless, during these periods the UVI values were still unusual as they also fell outside the 95% occurrence interval. This is typical of O_3 and UVI variations at these latitudes, as the Antarctic vortex frequently stretches and becomes more elliptic, while at the same time rotating around Antarctica with a typical rotation period of 20 days. During the vortex rotation the edges of an elliptic vortex pass twice over a given location like during the end of September and beginning of October 2009 with a time difference between both occurrences of about 10 days. This dynamical behavior explains the broad total O_3 column and UVI occurrence distribution

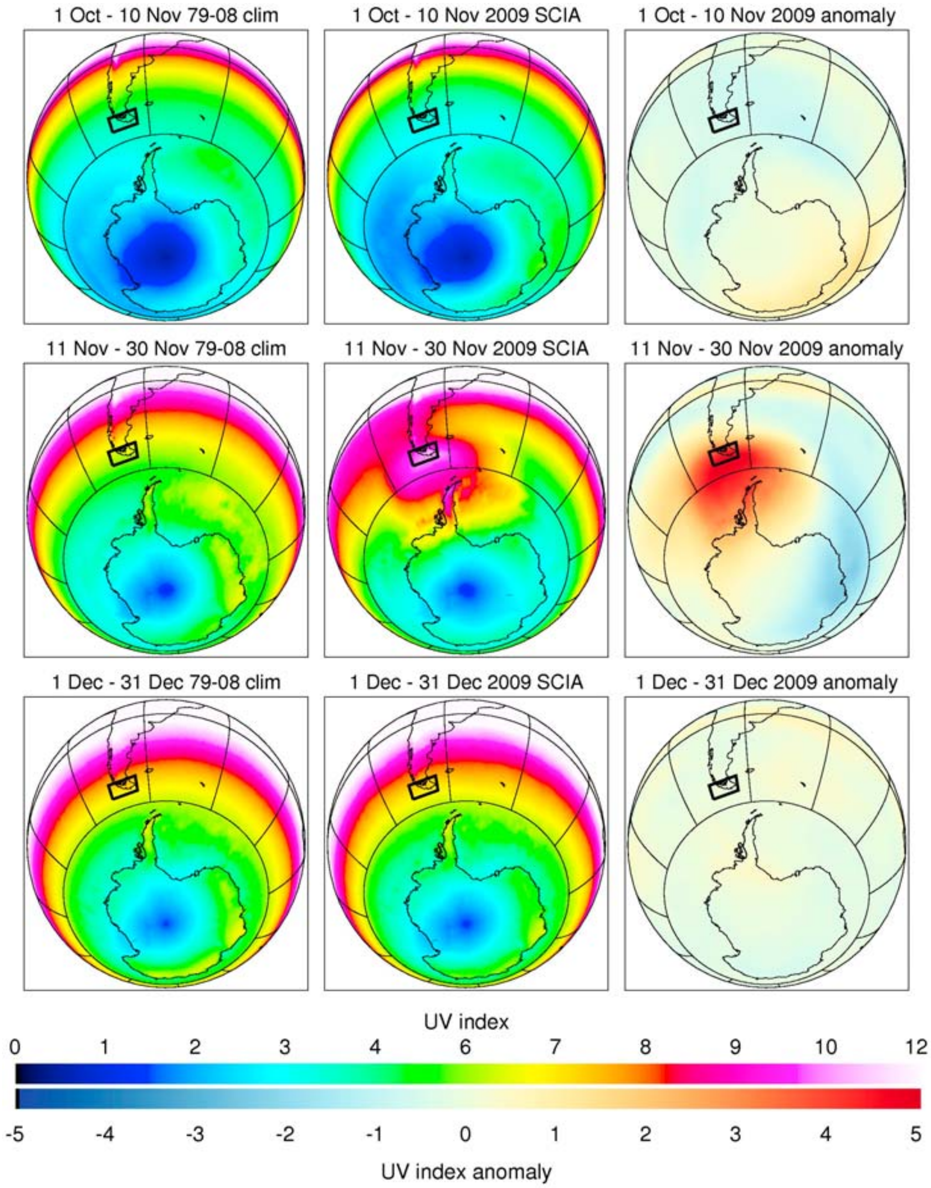

Figure 2. As Figure 1 but for UVI values. 1 UVI unit equals 25 mW/m^2.

as well as the increase in the width of the UVI distribution during the Antarctic O_3 hole season.

4. Validation Results and Discussion

[14] Figure 4 shows the time series and scatter plots of total O_3 columns and the UVI values measured from the ground and calculated based on assimilated SCIAMACHY measurements. The time zone of the ground stations is UTC minus 3 hours. Assimilated SCIAMACHY total O_3 columns are available every 6 hours. Hence, we take the mean of the 6 and 12 UTC assimilated columns for the comparison with the ground based observations. All three total O_3 column time series show the 20-day period in November 2009 with persistently small total O_3 columns. Furthermore, in the days leading up to this 20-day period, total O_3 columns are larger than the average of ~350 DU.

[15] The scatter plots show excellent agreement between ground-based and satellite-based total O_3 column measurements with correlations (R^2) varying between 0.92 and 0.96. The fit values of the regression are close to one, and biases are a few percent or less, which is excellent given the large dynamical range of the O_3 total columns. Punta Arenas shows a positive bias and Ushuaia a negative bias of the same magnitude; +11.9 and −9.7 DU, respectively. For Ushuaia, about half of this bias is related to a few outliers for which the SCIAMACHY O_3 columns are significantly larger than the ground-based measurements. These outliers coincide with a number of observations in September and early October where ground based UVI values are anomalously small compared to the satellite-based UVI values (see UVI for Ushuaia in Figure 4), suggesting that the ground-based measurements may have been affected by for example clouds and instrumental differences. Nevertheless, the biases are small compared to the average

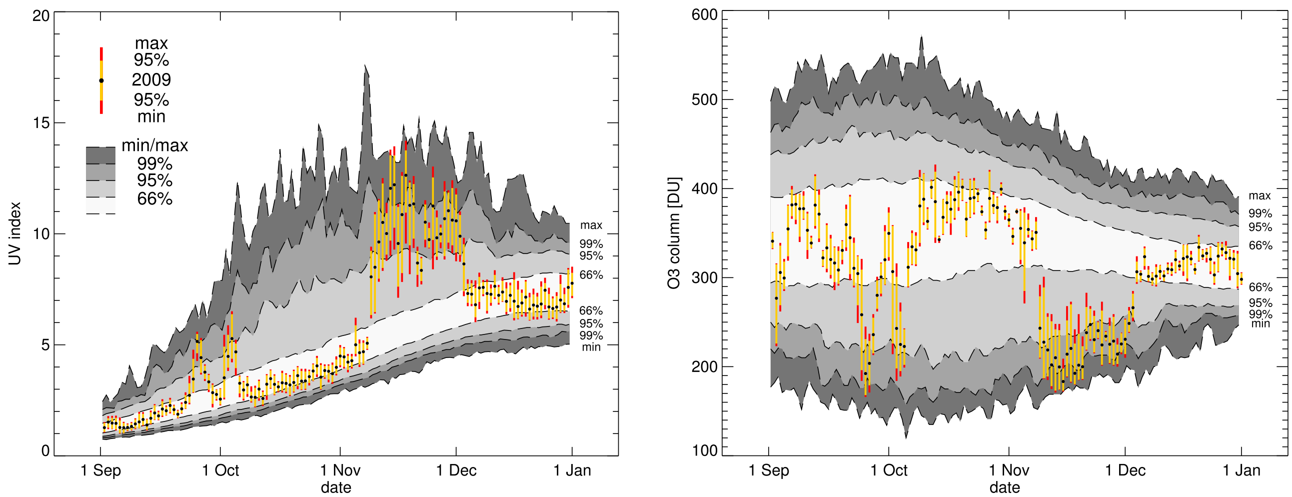

Figure 3. Time series of daily average (left) MSR total O_3 columns (in DU) and (right) UVI values for the period 1 September – 1 January. The shaded areas indicate the occurrence intervals of total O_3 columns and UVI values for 1979–2008 for the latitude band 52°–56°S. Occurrence intervals are calculated on a daily basis, and intervals are shown for 66%, 95% and 99% as well as the minimum and maximum MSR values. The numbers indicate the percentage of total O_3 columns or UVI values that fall within this range. The red/yellow bars represent the 2009 values for the area 52°–56° S, 77°–65° W (see Figures 1 and 2). Mean values are indicated by the black dots, the 2-σ root-mean-square of O_3 and UVI values within the area are shown by the yellow bars, and the minimum and maximum range within the area are indicated by the red bars.

total O_3 columns values as well as their dynamical range during this period.

[16] The UVI time series clearly show enhanced UVI values during the 20-day period in November 2009. The enhanced UVI values lie on top of a seasonal variation of UVI values because of decreasing solar zenith angles between September and December in this part of the world. Both ground-based measurements and satellite-based calculations for all three stations show UVI values of 10 to 14, which otherwise only occur equatorward of 40° latitude. The average UVI value at these locations increases from 5 to 6 during this period (see also Figure 3), so UVI values have approximately doubled compared to climatological conditions. The two short periods with small O_3 total columns at the end of September and beginning of October are also visible in the UVI. The regression between observed and modeled UVI shows large correlations (R^2) ranging from 0.8 to 0.94, and fit coefficients are between 0.89 and 0.97. Biases are a few percent, which again is excellent given the dynamical range of the UVI values.

[17] Finally, we note that the southern tip of South America lies right at the edge of the vortex during the November 2009 episode. Ushuaia is located further south and just within the vortex (see Figures 1 and 2), resulting in smaller total O_3 columns and larger UVI values compared to Punta Arenas and Rio Gallegos. Due to the transient dynamical nature of the vortex edge total O_3 columns and UVI values can change rapidly around the vortex edge. Evaluation of total O_3 columns and UVI values shows that during November 2009 the differences between bordering grid cells is much larger than average, with a rms of 20 DU for total O_3 columns and more than one UVI value (normal rms values are about 5 DU for total O_3 columns and 0.1 for UVI). Hence, representation errors may explain part of the differences between satellite and ground-based total O_3 column and UVI values in Figure 4, but this would require further investigation of individual events, which is beyond the scope of this paper. At locations further south, where the vortex edge is usually located, variability of total O_3 column and UVI values strongly decreased as this area was at the heart of the vortex rather than at the edge in this period.

5. Summary

[18] An analysis has been made of satellite and ground-based total O_3 column measurements during the Antarctic O_3 hole season in 2009, as well as a validation of UVI calculations using satellite-based total O_3 columns.

[19] Analysis of 1979–2008 MSR total O_3 columns and UVI values between 52°S and 56°S shows that for each day in this 20-day period the small total O_3 column and large UVI values are close to or outside the 5% occurrence interval. The occurrence of such small total O_3 columns and large UVI values for 20 consecutive days from 11–30 November 2009 is unprecedented. Hence, this particular event was unique in the history of the O_3 hole since 1979.

[20] The appearance of this event over populated regions made it even more relevant, and the presence of three ground-based O_3 and UV measurement stations provides an excellent opportunity for validation.

[21] An excellent agreement was found between both satellite-based and ground-based O_3 column measurements for three stations on the southern tip of South America. The comparison of satellite-based calculations and ground-based measurements of the UVI shows a similar excellent agreement with correlations (R^2) ranging from 0.80 to 0.96 and the ordinary linear regression shows values between 0.89 and 0.97. Despite the fact that the algorithm for calculating UVI values using satellite total O_3 column measurements was never developed for such extreme conditions, i.e., small total O_3 columns in combination with medium

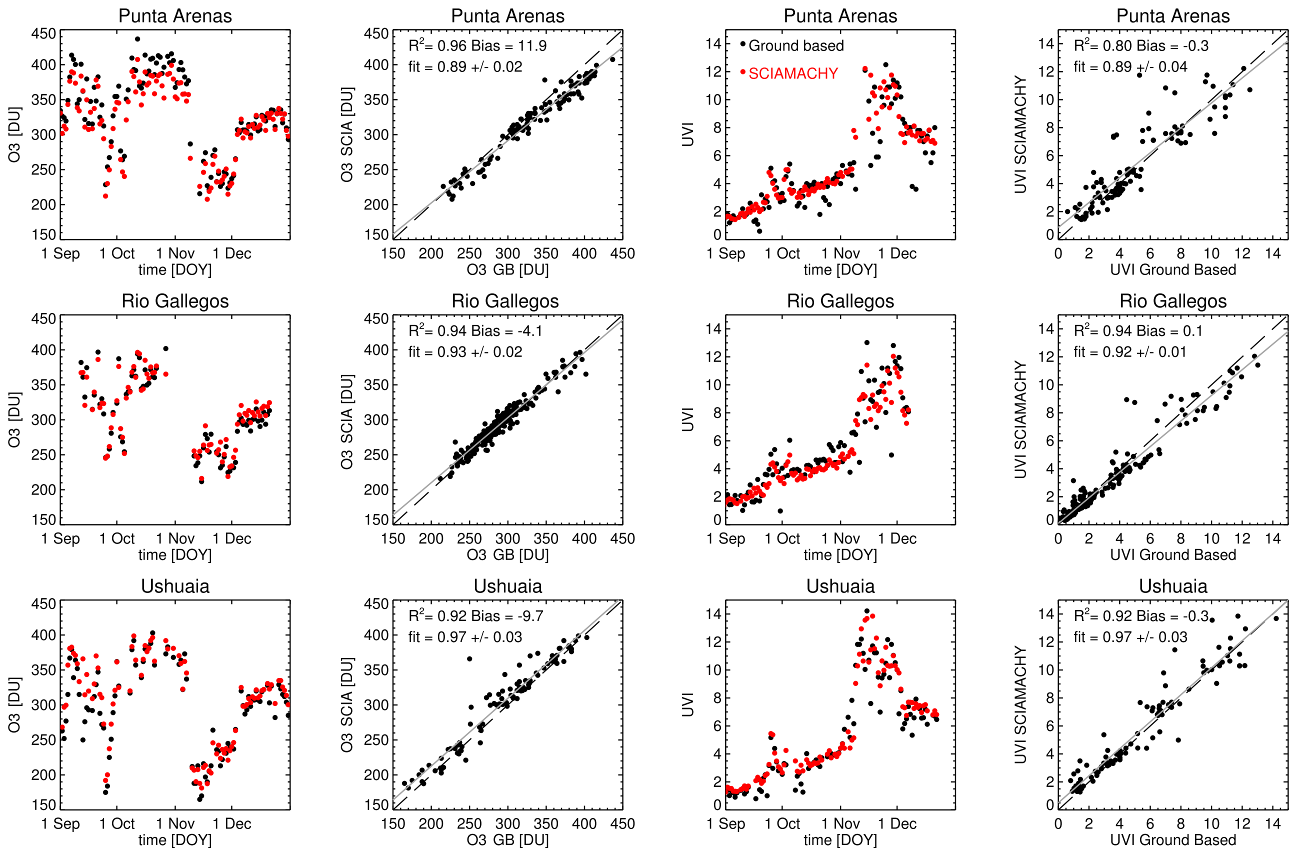

Figure 4. Time series for 2009 of ground-based and satellite measurements of total O_3 columns (first column; in DU) and ground-based UVI measurements as well as satellite total O_3 column based UVI values (third column) and the corresponding scatter plots (second and fourth column) for the three locations on the southern tip of South America, summarized in Table 1. The fit values in the scatter plots are calculated for an ordinary linear regression.

solar zenith angles, the algorithm is able to produce correct UVI values for such conditions.

[22] **Acknowledgments.** The work performed was partly financed by Netherlands Space Office within the SCIAVISIE project. The authors thank the Japan International Cooperation Agency (JICA), for their support in the experimental site in Río Gallegos. Special thanks also to Manuel Cupeiro, Chief of GAW Ushuaia and Maria Elena Barlasina for their support.

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