

# Antarctic network of lamp-calibrated multichannel radiometers for continuous ozone and uv radiation data

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## Abstract

Three NILU-UV multichannel radiometers have been installed in 1999 at the Argentinian sites of Ushuaia (54S), Marambio (64S) and Belgrano-II (77S) in order to continuously monitor UV radiation, photosynthetically active radiation and total ozone. The measurements were established by INM, Spain in collaboration with FMI, Finland, DNA-IAA, Argentina and CADIC, Argentina to observe and characterize the spatial and temporal evolution of ozone and ultraviolet radiation in the Antarctic region. Special attention has been given to the quality control and quality assurance of the measurements under harsh climatological conditions. The ozone and UV time series of 2000–2006 were calibrated using a polynomial fit for lamp measurements performed every second week all year round. The gaps in these data are minimal, with almost no data missing, and the data products are available from <http://www.polarvortex.org> in near real time. The data products include the erythemally-weighted UV, UVB and UVA radiation, photosynthetically active radiation (PAR), total ozone (O<sub>3</sub>) and a cloud parameter (CLT). For UV data, dose rates as well as daily doses are available; from these the maximum measured UV indices (UVI), during 2000–2006, were 12.0, 9.7 and 8.1 at Ushuaia, Marambio and Belgrano-II, respectively.

## 1 Introduction

Due to climate change, the expected recovery of the stratospheric ozone layer (Hadjinicolaou et al., 2005; Weatherhead and Andersen, 2006) may be endangered, as changes in the climate may serve to cool the stratosphere to temperatures favourable for ozone depletion (Butchart et al., 2000). All the factors that affect UV radiation, i.e., ozone, clouds, albedo (especially the effect of snow cover) and aerosols are related to climate change. Continuous quality-controlled Antarctic measurements of total ozone and UV radiation are therefore of great importance. It is evident that the ozone depletion area is variable and changes from year to year (WMO (World Meteorological

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Organization), 2007).

The Spanish contribution to Antarctic research began with the installation of three UV-VIS spectrometers at the Argentinian bases of Belgrano-II, Marambio and Ushuaia in 1994; in 1999 ozone soundings for the INTA (Instituto Nacional de Técnica Aeroespacial, Spain) were started at Belgrano-II, as well as the installation of three radiometers for the INM (Instituto Nacional de Meteorología, Spain), at the above-mentioned stations thanks to the existing agreements on scientific collaboration between the DNA/IAA (Dirección Nacional del Antártico/Instituto Antártico Argentino, Argentina) and INTA and INM, respectively. These complementary and coordinated networks of instruments are intended to observe and characterise the spacial and temporal evolution of the O<sub>3</sub>, NO<sub>2</sub>, OCIO and ultraviolet radiation in these regions during coming years. This project will provide and unique information to other Spanish and international groups involved in Antarctic biology research (Parrondo et al., 2007; Steck et al., 2007; Yela et al., 2003). The observation data are accessible to researcher at the web <http://www.spain.oracle-o3.org>.

In order to monitor the ozone profiles of the Antarctic, an Argentinian-Finnish co-operation project initiated regular ozone soundings at Marambio in November 1988. Nowadays they make a significant contribution to the regular ozone depletion reports, ozone bulletins, compiled by the WMO (<http://www.wmo.ch/pages/prog/arep/gaw/ozone/>), and have been used in scientific research (Taalas et al., 1997). The sounding data are available to all researchers from the data bases of WOUDC (World Ozone and UV radiation Data Center) and NILU (Norwegian Institute for Air Research). Since 1999, the ozone-hole-related activities at Marambio have been enlarged into Spanish-Argentinian-Finnish co-operative project, as it became one of the three year-around Antarctic region stations to measure simultaneously total ozone and UV radiation with NILU-UV multichannel filter radiometers.

Previously, in 1988, NSF (U.S. National Science Foundation) had established a measurement network comprising six high-latitude sites from the South Pole to Alaska (Bernhard et al., 2005). The NSF network in the Antarctic region includes Ushuaia

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(54°49' S, 68°19' W), McMurdo (77°50' S, 166°40' E), Palmer (64°46' S, 64°03' W), and the South Pole (90°00' S). NSF sites are equipped with scanning spectroradiometers (type SUV-100 or SUV-150B) and multichannel filter instruments (type GUV-511 or GUV-541). The NSF observations are freely available via the internet at <http://www.biospherical.com/NSF/>.

The Antarctic NILU-UV network by the Spanish-Finnish-Argentinian co-operative project is unique in the sense that no earlier UV network has linked the Antarctic and the European Arctic. The NILU-UV network travelling reference of FMI, described further in Sect. 2.2, can be used to compare and transfer the UV irradiance scale from one hemisphere to another. In addition to this, the station of Ushuaia belongs to both the NSF and our network. This makes solar comparisons possible, and all the stations of both of networks can be used for any study with knowledge of the irradiance scales. According to Lakkala et al. (2005), the irradiance scales of NSF and our network are within 5%.

The ozone and UV data from the NILU-UV network, documented here for the first time, are quality-controlled, continuous and have the potential for wide use among scientists. Recently, the results of the network were also used for the WMO ozone bulletin for the first time. The quality assurance of the network has been published earlier in Lakkala et al. (2005).

## 2 NILU-UV antarctic network

In 1999, an Antarctic network of multichannel NILU-UV instruments was established in order to measure real-time ground-based UV radiation and total ozone columns. The network was established by INM in collaboration with FMI, DNA-IAA and CADIC (Centre for Scientific Research, Argentina). The main objectives of the network are to observe and to characterise the spatial and temporal evolution of both the ozone and the ultraviolet radiation in the Antarctic region and to carry out dynamics studies of the Antarctic polar vortex. At the present time, the network has been consolidated, and

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this makes it possible to analyse how the daily evolution of the vortex affects the ozone and UV radiation. Great effort has been put into the quality control of the network data so that they can also be used for studies that require high accuracy in the data, e.g., climatological studies.

## 5 2.1 Stations

NILU-UV multichannel filter radiometers have been set up at three Argentinian Antarctic stations. The location of the stations with respect to the stratospheric polar vortex, and to the ozone depletion area, is the underlying motive for selecting the sites: Belgrano-II (77°52'29" S, 34°37'37" W, 50 m a.s.l.) is mostly located inside the vortex; Marambio (64° 14' S, 56° 38' W, 200 m a.s.l.) is at various times inside, on the edge of, or outside the vortex; while Ushuaia (54°49' S, 68°19' W, 50 m a.s.l.) is mostly outside the vortex. All these bases are permanent and manned all the year round. At all the stations, the NILU-UV radiometers are installed on the roofs of the permanent buildings of the bases.

15 The Argentinian city of Ushuaia is the southernmost city in the world, and is located on Grande Island of the Land of the Fire. Ushuaia is affected by the Antarctic ozone loss, especially during an event in which it is beneath the vortex, and for this reason it is one of the most populated towns affected by the yearly ozone loss. Ushuaia is the capital of the Land of the Fire, and it extends over the slopes of the Martial Mounts. The measurement instruments are in the facilities of the CADIC. This Center was created 20 on the 9 of April, 1969, and belongs to the National Council of Scientific and Technical Research (CONICET). In Ushuaia, the weather is variable all year round, with the lowest daily mean temperature of 1°C occurring at the end of July and beginning of August.

25 Marambio and Belgrano-II are two of the six Argentinian bases that remain open all year long, and belong to IAA-DNA. They were set up in 1969 and 1979, respectively. Marambio is located on the Island of Seymour, approximately 1.6 km to the NE of the Island of Cerro Nevado on the southern margin of the gulfs of Erebus and Terror in

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the Sea of Weddell. This base is located on a plateau 14 km in length and 8 km wide, 200 m a.s.l., and hosts many other scientific instruments, e.g., for carrying out regular ozone soundings and aerosol measurements. Sometimes the air masses there originate in midlatitudes and have high total ozone column values, while at other times 5 polar air masses with only little ozone affect the area. Belgrano-II is located in Nunatak Bertrab, on the Confin Coast (Land of Coast), Sea of Weddell. Because of its location, this base is one of the most important observatories for the study of the ozone destruction during the austral spring, but it is only accessible once a year, during the austral summer, and then only with the aid of the "Icebreakers Almirante Irizar". The weather 10 at Belgrano-II is harsh. The wind may reach 200 km/h, and the measured maximum and minimum temperatures range from -2°C to -4°C. Due to the high latitude, the sun does not rise at all for 4 months of the year.

## 2.2 Instrument

The NILU-UV 6T radiometer is a filter instrument with five UV channels, with central 15 wavelengths at around 305, 312, 320, 340 and 380 nm, and bandwidths of around 10 nm at full-width half-maximum (FWHM). A sixth channel measures the photosynthetic active radiation (PAR) in the 400–700 nm wavelength region. The radiometer has a Teflon diffuser, silicon detectors, high-quality bandpass filters and is temperature-stabilized to 40°C. One-min averages of measured irradiances and detector temperatures are recorded. The measurements can be used to retrieve UV-B, UV-A, erythemally -weighted UV radiation and the total ozone column, as well as to provide cloudiness information, using the method described by Dahlback (1996). The characteristics 20 of the instrument are described in more detail in Höiskar et al. (2003).

During the period 2000–2006, the NILU-UV #012 and NILU-UV #011 radiometers 25 have been measuring continuously at Ushuaia and Marambio, respectively, while at the Belgrano-II base, three different instruments have been used for measurements: NILU-UV #009, NILU-UV #010 and NILU-UV #023 (Table 1). Due to technical problems during the exchange of instruments in Belgrano-II, the NILU-UV#023 has been

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measuring in this site since 2004 until now.

### 2.3 Quality control (QC) and Quality assurance (QA)

The quality control and quality assurance of the network is based on regular lamp measurements and, for UV radiation measurements, on a travelling reference (Lakkala et al., 2005). An important part of the quality control has been to train the station operators; this training is repeated every second year. The operators perform daily checks that include timing control and cleaning of the diffuser. The levelling of the instrument is also regularly checked. The operators perform lamp tests and dark current measurements, as well as solar comparisons between the station instrument and the travelling reference NILU-UV radiometer.

#### 2.3.1 Lamp measurements: QC

The quality control for the site instruments consists of 100 W OSRAM Radium lamp measurements and dark current measurements. Two lamps are measured every two weeks and a third lamp is measured on every third calibration to exclude possible lamp drift. During the calibration, the power supply of the lamp is controlled with software that keeps the lamp intensity constant. Lamp tests are also made before and after each solar comparison to determinate the stability of the reference NILU.

In order to study the stability of the NILU-UV, the lamp measurement time series for each instrument was calculated. The normalized averages of lamp measurements at Ushuaia, Marambio and Belgrano (2000–2006) are shown in Fig. 1. The results of all the six channels of the radiometer are shown. In each case, the lamp averages were normalized with the first calibration, in order to observe any changes in the sensitivity of the channels.

When we have four successive instruments at one station, as at Belgrano-II, it is not always possible to perform a direct comparison of the two instruments being interchanged. In this case, the last lamp calibration of the leaving instrument and the

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first lamp calibration of the replacing instrument are used to adjust the calibration scales of the instruments. As the instruments are manufactured using the same filter batch, we convert the measurements of the lamps for each instrument to that of the other one before it. In this way, all calibrations are referenced to the first instrument NILU-UV #009 and a unique lamp series is used for all the NILU-UV radiometers at Belgrano-II.

Changes of more than 50% in the sensitivity of some of the channels have been observed in all the instruments. The channels with the largest drift are #3 and #4 in all the radiometers. To obtain the UV dose rates and ozone, the observed values have been corrected for the drift of the channels. The procedure used is shown in Sect. 3 and its validation using ozone measurements from different sources was described in Torres et al. (2002).

#### 2.3.2 Travelling reference: QA

The quality assurance of the UV measurements of the whole network is based on a travelling reference NILU-UV which makes it possible to maintain the absolute irradiance scale of the different stations. The irradiance scale can be transferred using the results of solar comparisons between the reference NILU-UV and the NILU-UV of the station (Lakkala et al., 2005). The travelling reference visits Ushuaia three times and Marambio twice during the spring-summer-autumn season. Visits of the travelling reference to Belgrano-II are impossible, due to the inaccessibility of the site for most of the year. Access is possible, using an icebreaker, only during the summer, when the NILU-UV at Belgrano is replaced each year by another, well-calibrated, NILU-UV, of which the calibration is traceable to the irradiance scale used at Marambio and Ushuaia.

The travelling reference is calibrated every year or every second year. During the winter period of the Antarctic, the reference NILU-UV measures in the Arctic, and may attend intercomparison campaigns. This makes possible the comparison of UV measurements performed in both hemispheres using the same irradiance scale. Table 2 shows the ratios between the erythemally-weighted UV dose rates retrieved from the reference NILU-UV, network NILU#012 and those measured by the NSF-network SUV-

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spectroradiometer at Ushuaia. The results are shown for the lowest SZA in almost clear-sky conditions. A cosine correction of 5% has been assumed for the SUV-data (Bernhard, G., personal communication, 2004). The results show compatibility within the measurement uncertainties. The reference instrument for the calibration of the reference NILU-UV is the Bentham spectroradiometer of the NRPA, whose irradiance scale is traceable to the National Institute of Standards and Technology (NIST) via the laboratory of SP, the Swedish National Testing and Research Institute (Johnsen et al., 2002). The irradiance scale of the SUV-spectroradiometer is also traceable to the NIST via 200 W lamps (Bernhard et al., 2006).

### 3 Measurements

The total ozone column and the biologically-effective UV rates are determined using the method described by Dahlback (1996).

The total ozone column ( $\Omega$ ) is determined by comparing a calculated irradiance ratio, ( $N'$ ), with the corresponding measured ratio ( $N$ ), Eq. (1),

$$N(\theta, \Omega) = V_i(\theta, \Omega) / V_j(\theta, \Omega) \quad (1)$$

where  $V_i$  and  $V_j$  are the irradiances in two channels with a different sensitivity to ozone absorption. We have used the ratio between the irradiances at 320 nm ( $V_i$ ) and 312 nm ( $V_j$ ), low and high ozone absorption, respectively. A radiative-transfer model (Mayer and Kylling, 2005) is used to determine a look-up table of ratio  $N'$  as a function of solar zenith angle ( $\theta$ ) and ozone ( $\Omega$ ). The look-up table also depends on the atmosphere, ozone profile, aerosols, clouds and surface albedo.

The UV dose rates ( $D$ ), Eq. (2), are determined as a linear combination of the irradiances, represented by the NILU-UV raw data ( $V_i$ ) obtained from the five UV channels ( $i$ ).

$$D = \sum_{i=1}^5 a_i V_i \quad (2)$$

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In order to obtain the coefficients of the linear combination ( $a_i$ ), spectroradiometer-based calibration and radiative-transfer calculations are needed (Dahlback, 1996).

To apply this method, it is necessary to correct the drift shown by the quality control. A polynomial fit is calculated with the normalized average of lamp measurements to obtain a daily correction coefficient for each channel and instrument (Fig. 1). With these coefficients, all the raw data are referenced to the first absolute calibration. This first calibration of all the network instruments was performed by the manufacturer at the Izaña Atmospheric Observatory, Izaña (Tenerife, Spain), in 1999. Following that, NILU-UV #012, NILU-UV #011 and NILU-UV #009 were set up at Ushuaia, Marambio and Belgrano-II, respectively. All measurements are referenced to the first instrument NILU-UV #009 at Belgrano-II and all the other instruments are converted to this standard. The drift is corrected using its normalized lamp average, as at the other stations. With this correction method all the three stations maintain the scale of the manufacturer calibration; this absolute scale can be changed using the travelling reference in Ushuaia and Marambio and in Belgrano we can use the NILU#023 compared with QASUME unit (Gröbner et al., 2005) just before its setup at Belgrano as is described by Meinander et al. (2004).

## 4 Results and discussion

### 4.1 Ozone and UV time series

As the NILU-UV instrument gives a reading every min, it is perfect for monitoring rapid changes in the atmosphere. The total ozone changes during a day can be followed, as well as the exact UV daily doses, even during days with rapidly-changing cloudiness. The time series of 2000–2006 covers almost all the days of the year, with a minimal amount of missing data.

The total ozone and maximum daily UV index time series are shown in Fig. 2 for Ushuaia, Marambio and Belgrano-II. The connection between the total ozone and UV

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radiation is clearly seen in the time series. Maximum spring-time UV values are mostly connected with low ozone values. The daily evolution of the stratospheric polar vortex can also be studied from our measurements. The location of the polar vortex and its associated low ozone values can move from day to day and have an effect even at the latitudes of Ushuaia. This event is usually recorded as high UV values at Ushuaia. During 2000–2006, the highest UV index value measured at Ushuaia was 12.0 on 27 Nov 2003. For the same period the highest UV index at Marambio was 8.1 on 04 Dec 2001 and 9.7 in Marambio on 22 Oct 2000.

The UV daily doses at three stations are shown in Fig. 3 during spring-time the daily doses are similar, even though the latitude of Marambio and Belgrano would suggest significantly lower UV daily doses comparing with Ushuaia. High daily doses are strongly connected to low ozone values at Marambio and low cloudiness at Belgrano. The monthly means of erythemally-weighted UV daily doses are shown in Table 3.

#### 4.2 Web site implementation

The NILU-UVs at the bases are controlled by individual workstations, in which the raw data are stored. The raw data are remotely harvested from the logging computers, and all data products are calculated and presented on the webpage <http://www.polarvortex.org> as soon as they are available. These data available from the web are thus real-time data and are considered to be provisional. Any user of the data is kindly asked to contact the web-master to get the latest QC/QA information. Two types of data are available for downloading: daily course data (of ozone, UVI, CIE, UVA, UVB, UVA/UVB CLT, PAR ) and summary files with the solar noon data. For both, two data versions, V1.1 and V1.2 exist, depending on the last available lamp test. V1.1 contains data extending up to the last-available stability check, while V1.2 is produced when the data has been processed using both the previous and the following lamp test. V1.1 is updated daily and V1.2 every two weeks after the lamp test has been performed.

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### 5 Conclusions

In this paper we have presented the Antarctic NILU-UV network established in 1999 as a joint Spanish-Finnish-Argentinian co-operation. Three NILU-UV multichannel radiometers have been installed at the sites of Ushuaia, Marambio and Belgrano-II. Special attention has been given to the quality control and quality assurance of the data. Initial and refresher training is provided for the operators, and regular lamp tests are performed in order to monitor the stability of the instruments. Severe drift of the channels of the multifilter radiometers has been detected and corrected in order to produce homogenized time series. The time series contain daily UV and ozone data since 2006 and are available online at <http://www.polarvortex.org>. The data contain UVB, UVA, erythemally-weighted UV dose rates, PAR and cloud information, and ozone data. Daily summaries of UV data are also available.

It is of major importance to continue long-term measurements of ozone and UV in the Antarctic region; extension of the existing valuable data series will enable monitoring of future changes of all the relevant environmental factors, and ensure the availability of these data to the research community representing various fields of science. We have found the NILU-UV radiometer to be a good instrument for operation in harsh environments, but that QA/QC are essential to monitor the drift in the sensitivity of the channels. In the future, we plan to include the Norwegian Troll station (72°0' S, 2°32' E) in the network and its data in the web pages.

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**Table 1.** NILU-UV radiometers set up in the Base Belgrano-II.

Instruments	Date	Date
NILU-UV #009	02/03/2000	26/02/2001
NILU-UV #010	27/02/2001	23/02/2002
NILU-UV #009	24/02/2002	25/02/2003
NILU-UV #010	25/02/2003	03/02/2004
NILU-UV #023	04/02/2004	To present

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**Table 2.** The ratios of erythemally-weighted UV dose rates between the reference NILU-UV #008 the network NILU-UV #012 and the SUV-spectroradiometer at Ushuaia during 2000–2006.

Date	SZA	SUV/NILU #008	SUV/NILU #012
01/12/1999	34	0.95	
15/02/2000	40	0.97	1.04
06/05/2000	70	1.03	1.07
27/10/2000	40	0.99	0.96
09/02/2001	40	0.98	1.04
18/05/2001	74	0.99	1.08
17/10/2001	34	0.98	0.96
14/04/2002	65	0.97	1.01
11/11/2002	40	0.97	
22/02/2003	45	0.96	1.01
17/10/2003	45	0.99	1.01
16/01/2004	52	0.95	1.00
10/12/2004	40	0.96	0.94
01/03/2005	48	1.03	1.01
28/11/2005	38	0.96	0.96
03/03/2006	48	0.97	0.92
15/11/2006	40	0.99	0.94

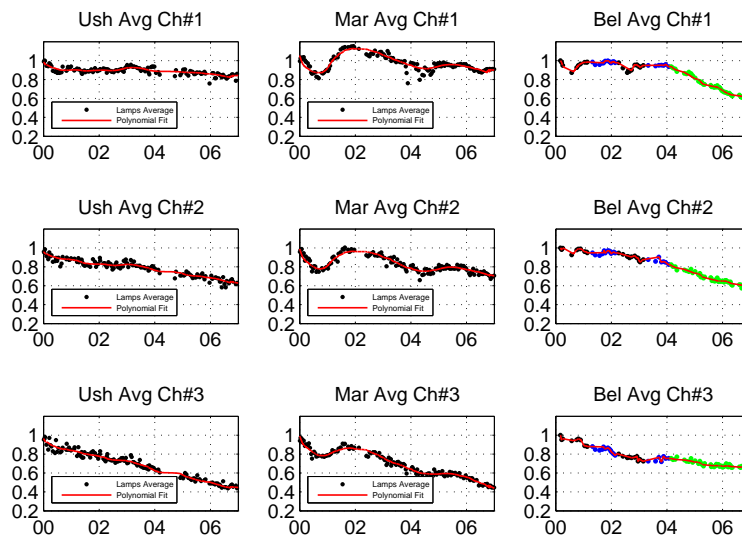
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**Table 3.** Monthly mean Erythemal Daily Dose ( $\text{KJ/m}^2$ ) for the three stations, even though with the different latitude of the stations the values are comparable and even higher on the southernmost station Belgrano.

Month	Ushuaia (54 S)	Marambio (64 S)	Belgrano (77 S)
Jan	3.1	2.6	2.7
Feb	2.5	1.7	1.5
March	1.3	0.8	0.4
April	0.5	0.2	0.1
May	0.2	0.0	–
June	0.1	0.0	–
July	0.1	0.0	–
Aug	0.3	0.2	0.1
Sep	1.0	1.0	0.5
Oct	2.0	2.0	2.0
Nov	2.7	2.5	3.0
Dec	3.3	2.8	3.1

3399



**Fig. 1.** Lamp measurements time series of Ushuaia, Marambio and Belgrano during 2000–2006. Results of the six channels are shown together with the average of the lamps and the polynomial fit. The colors in Belgrano series indicate the different instruments used.

3400

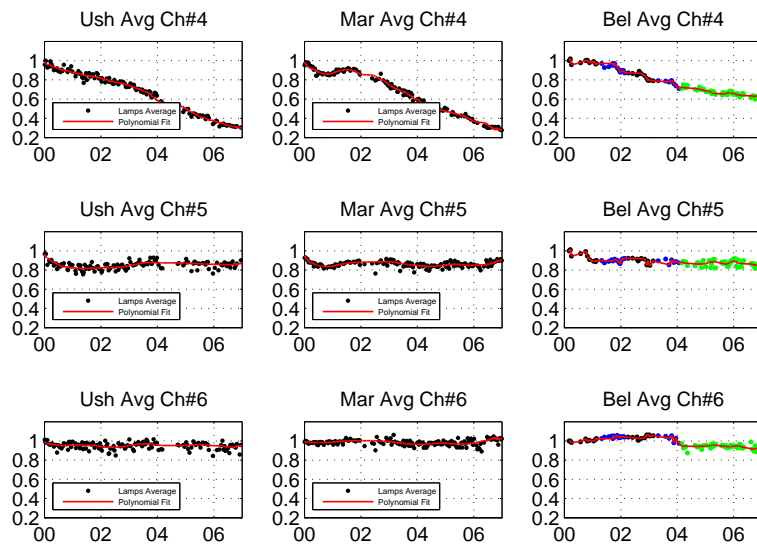


Fig. 1. Continued.

3401

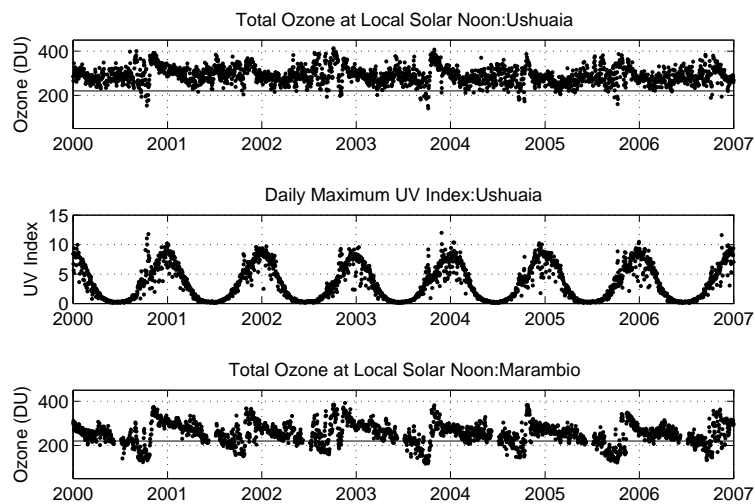


Fig. 2. Time series of total ozone and UV index at Ushuaia, Marambio and Belgrano-II during 2000–2006. Horizontal line in ozone plots indicate the level Ozone hole level off 220 Dobson Units.

3402

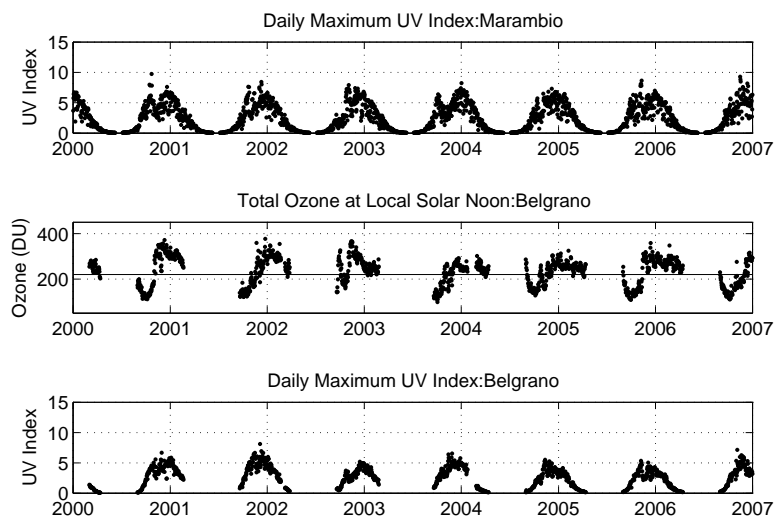


Fig. 2. Continued.

3403

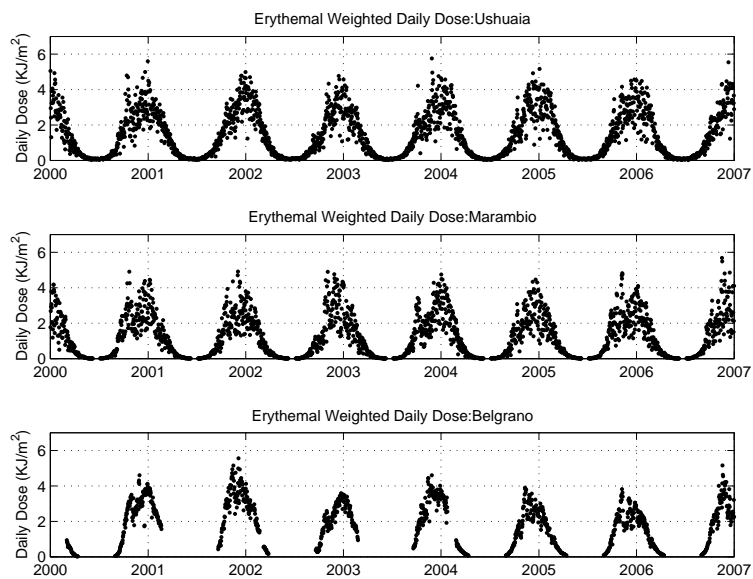


Fig. 3. Time series of Erythemal Daily Dose Ushuaia, Marambio and Belgrano-II during 2000–2006.

3404