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The world's highest levels of surface UV

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Raul R. Cordero,*[a] Gunther Seckmeyer,[b] Alessandro Damiani,[a] Stefan Riechelmann,[b] Juan Rayas,[a] Fernando Labbe[c] and David Laroze[d]

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Chile's northern Atacama Desert has been pointed out as one of the places on earth where the world's highest surface ultraviolet (UV) may occur. This area is characterized by its high altitude, prevalent cloudless conditions and relatively low total ozone column. Aimed at detecting those peak UV levels, we carried out in January 2013 ground-based spectral measurements on the Chajnantor Plateau (5100 m altitude, 23°00′S, 67°45′W) and at the Paranal Observatory (2635 m altitude, 24°37′S, 70°24′W). The UV index computed from our spectral measurements peaked at 20 on the Chajnantor Plateau (under broken cloud conditions) and at 16 at the Paranal Observatory (under cloudless conditions). Spectral measurements carried out in June 2005 at the Izaña Observatory (2367 m altitude, 28°18′N, 16°30′W) were used for further comparisons. Due to the differences in sun–earth separation, total ozone column, altitude, albedo, aerosols and clouds, peak UV levels are expected to be significantly higher at southern hemisphere sites than at their northern hemisphere counterparts.

1. Introduction

Increases in surface ultraviolet (UV) irradiance may lead to adverse effects on the biosphere including terrestrial and aquatic ecosystems as well as public health.[1,2] The UV index (UVI) is an international standard measure of the UV level that can lead to an erythemal or sunburning response in humans. Although the UVI was originally conceived as a daily measure of the peak at solar noon, it is now commonly considered a continuous measure. The UVI is evaluated by integrating the spectral UV irradiance weighted by using the so-called McKinlay–Diffey Erythema action spectrum.[3,4] The World Health Organization considers that UVI values greater than 11 stand for extreme risk of harm. While some of the adverse effects of the UV irradiance may be strictly proportional to cumulative UV dose, others may relate to extreme UV events.[5]

Surface UV depends on the solar zenith angle (SZA), total ozone column, cloudiness, ground reflectivity (albedo), local aerosols, altitude, and the sun–earth-distance. Because of the different geographic distributions and magnitudes of these parameters, inter-hemispherical differences in surface UV can occur.[6] For example, the elliptical orbit of the earth around the sun makes the earth closer to the sun in the southern hemisphere (SH) summer compared with the corresponding season of the northern hemisphere (NH). Moreover, both the overall ozone amount and the aerosol loading are lower in the SH.[5,6] Therefore, the highest surface UV is expected to occur in summer at high altitude sites in the SH near the Tropic of Capricorn, *i.e.* Chile's northern Atacama Desert. This area is characterized by high altitude, prevalent cloudless conditions, and a relatively low total ozone column.

The albedo of bright deserts or winter snow over surrounding mountains has an effect on surface UV.[7] However, as UV reaches peak summer levels in the Atacama Desert the influence of natural atmospheric aerosols (wind-blown dust) is presumably greater. Due to the dry and arid conditions, the load of aerosols at desert locations tends to be significant. For example at sites in North Africa, the aerosol optical depth (AOD) is typically higher than 0.15 at 500 nm.[8] The AOD in the visible range measured at desert sites in northern China ranges from 0.24 to 0.36.[9] In the case of the Atacama Desert no measurements of the local AOD in the UV range have previously been reported.

Since desert areas are typically characterized by clear conditions,[10,11] the role of clouds is normally ignored. However, peak UV can be significantly affected by cloudiness. Clouds generally reduce surface UV irradiances, although the magnitude of this effect is highly variable depending on cloud amount and coverage, cloud cell morphology, particle size distributions and phase (water droplets and ice crystals), and possible in-cloud absorbers (esp. tropospheric ozone). Although heavily overcast conditions can reduce surface UV irradiance by 90%,[12,13] UV irradiances recorded under cloudy conditions can be enhanced compared to clear sky conditions, as for example when both direct and cloud-scattered sunlight (*e.g.* in the presence of bright broken clouds) reach the

[a]*Universidad de Santiago de Chile, Ave Bernardo O'higgins 3363, Santiago, Chile. E-mail: raul.cordero@usach.cl*
[b]*Leibniz Universität Hannover, Herrenhäuser Str. 2, 30419 Hannover, Germany*
[c]*Universidad Técnica Federico Santa María, Ave. España 1680, Valparaíso, Chile*
[d]*Instituto de Alta Investigación, Universidad de Tarapacá, Casilla 7D, Arica, Chile*

surface.[14–17] Indeed, NH's highest levels of surface UV have been measured in Mauna Loa, Hawaii (3400 m altitude, 19°30′N)[18] and in Tibet (5000 m altitude, 29°N).[19] In both cases, the authors reported that during summer the UVI exceeded 15 under cloudless conditions, and occasionally exceeded 20 under broken cloud conditions.

Although satellite-derived data indicate that peak UVI values often exceed 20 in Chile's northern Atacama Desert, the derivation of surface UV from satellites is based on the measurement of backscattered UV radiation. Therefore, satellites are unable to fully capture the effects of a complex topography, tropospheric aerosols and clouds. Prior efforts have shown that satellite-derived estimates of surface UV are biased high, particularly at polluted sites.[20–29] Oyanadel *et al.*[30] also reported a poor correlation between the AOD, derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite instrument,[31] and AOD data measured by sunphotometers of the AERONET network.[32] These facts complicate the evaluation of surface UV irradiance using satellite readings and promote ground-based measurements. However, long-term UV series are limited worldwide.

The Network for the Detection of Atmospheric Composition Change (NDACC)[33,34] maintains a long-term database of quality-controlled UV data only from a small number of observation sites. The number of locations in the SH is even lower than in the NH and no quality-controlled spectral measurements are available in the Atacama Desert.

In this paper, we report on the first quality-controlled spectral UV measurements in Northern Chile carried out by using a double monochromator-based spectroradiometer. We measured on the Chajnantor Plateau (located at 5100 meters above the sea level in the Atacama Desert, 50 kilometers to the east of San Pedro de Atacama, 23°00′S, 67°45′W) and at the Paranal Observatory (located on Cerro Paranal at 2635 m altitude, 120 km south of Antofagasta, 24°37′S, 70°24′W). Spectral measurements carried out in June 2005 at the Izaña Observatory (located on Tenerife island at 2367 m above sea level, 28°18′N, 16°30′W) were used for further comparisons.

2. Background

2.1. Ground-based spectral UV measurements

Quality-controlled measurements of the surface UV require double monochromator-based spectroradiometers. Instruments developed according to the specifications defined by the World Meteorological Organization (WMO)[34] and the Network for the Detection of Atmospheric Composition Change (NDACC)[33] can produce a radiometric stability better than 1%.[35–37]

The accuracy of NDACC-certified instruments has been tested by intercomparison campaigns (involving several instruments[33]) and by the comparisons with spectral UV calculations.[38–41] The differences between NDACC-certified instruments are normally within the bounds defined by the involved standard uncertainties; up to 4% for UVA wavelengths and up to 10% for UVB wavelengths.[37] By comparison, broadband instruments calibrated by a spectroradiometer have uncertainties in the range 7%–16%.[42]

The UV Index (UVI) can be retrieved from spectral measurements by integrating the UV spectra (weighted by the Erythema action spectrum[3]). The standard uncertainty of UVI values computed from measurements by NDACC-certified instruments has been estimated to be less than about 5%.[4] The uncertainties of erythemal daily doses (computed also from spectral measurements) are expected to be similar.

2.2. Satellite products

Satellite estimates of the total ozone column (TOC) data have been validated using ground-based measurements.[43,44] However, under specific conditions (*e.g.*, high SZA conditions, high surface albedo) and/or for Polar Regions (*e.g.*, at high latitudes), a poorer agreement has been reported.[45]

Satellite estimates of the surface UV are normally derived from other products (*e.g.*, ozone, albedo, aerosols and cloud cover) using radiative models and then uncertainties tend to be higher,[46] especially for partly cloudy and overcast conditions.[47]

Validations of OMI-derived data have generally reported that the UV estimates are biased high.[20–29] Among the factors that explain the overestimation have been pointed out the limited spatial resolution[24,26] and the lack of sensitivity of OMI to the boundary layer.[24,25,27,29]

2.3. Modeled UV data

Surface UV can also be computed using radiative transfer models[48] from a set of parameters that include the albedo, the total ozone column, the SZA, as well as the characteristics of aerosols and clouds. Under cloudless conditions and for UVB wavelengths, Cordero *et al.*[49] have estimated that the uncertainties of model products can be up to 20% for sites with very large aerosol load, and up to 9% for clear sites.

Under cloudless conditions comparisons with ground-based measurements have validated model products.[38–40] However, the characterization of the cloud effect remains difficult.

3. Measurements

Measurements in northern Chile were carried out by using a double monochromator-based spectroradiometer (subsequently referred to as USACH spectroradiometer), normally based at the Universidad de Santiago de Chile (USACH, Chile). Measurements in Tenerife were carried out by using a NDACC-certified double monochromator-based spectroradiometer (in what follows referred to as IMUK spectroradiometer), from the Institut für Meterologie und Klimatologie (IMUK, Leibniz Universität Hannover, Germany). The USACH spectroradiometer is based on a double monochromator Bentham DMc150F-U, 150 mm focal length, and 1800 lines per mm grating. The IMUK spectroradiometer is based on a double monochromator

Bentham TMc300, 300 mm focal length, and 2400 lines per mm grating.

In both measuring systems, a photomultiplier (PMT) is used as a detector; the input optics and the double monochromator are connected using UV transmitting fiber optic. Both systems are operated within temperature controlled weatherproof boxes. In accordance with international recommendations[34] the stability of the instruments was checked by using a set of halogen lamps.

In the case of the measurements in northern Chile, the USACH spectroradiometer was set to sample the irradiance every 1 nm in the range 280–600 nm; the scans were carried out at a 15 min interval. In the case of the measurements in Tenerife, the IMUK spectroradiometer was set to sample the irradiance every 0.5 nm in the range 290–450 nm; the scans were in this case carried out at a 30 min interval.

Fig. 1 shows the UVI values computed from the spectra measured on the Chajnantor Plateau on 13–1701.2013 (a); at the Paranal Observatory on 09–11.01.2013 (b); and at the Izaña Observatory on 08–10.06.2005 (c). The OMI-derived estimates of the noontime UVI are also shown in Fig. 1 (see crosses). However, note that unfortunately in the case of Paranal, only the OMI estimate on 09.01.2013 is available due to gaps in the OMI time series.

Ground-based measurements in Fig. 1 show that the UVI peaked at 20 on the Chajnantor Plateau (on 13.01.2013, broken cloud conditions), 16 at the Paranal Observatory (on 09.01.2013, cloudless conditions), and 13.5 at the Izaña Observatory (on 08.06.2005, cloudless conditions). It is worth highlighting the fact that the peak UVI on the Chajnantor Plateau was measured under broken cloud conditions. The maximum UVI under cloudless conditions was significantly lower: 18. The substantial differences in Fig. 1 between peak UV values at the compared geographical locations are not unexpected. McKenzie *et al.*[6] showed that peak UVI values in New Zealand are about 40% higher than those at similar latitudes in North America.

In order to compare UV levels in northern Chile and Tenerife, the measured spectra were linearly interpolated. Then, we calculated the UVB (290–315 nm), the UVA (315–400 nm), and the UVI for certain common SZAs. Fig. 2a shows the ratio between the UV integrals at the Izaña Observatory (on

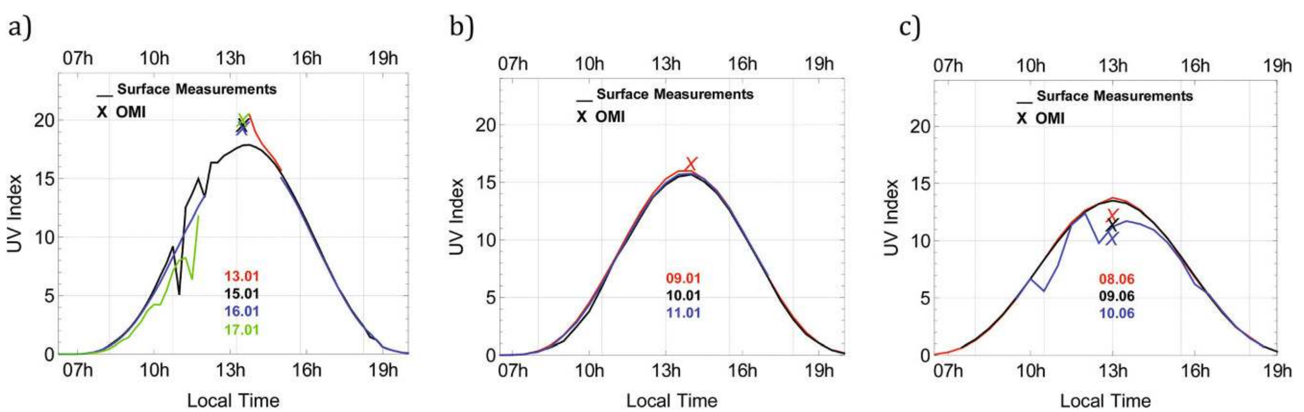

Fig. 1 UVI computed from ground-based measurements (see lines) and OMI noontime estimates (see crosses). (a) On the Chajnantor Plateau on 13.01.2013 (red), on 15.01.2013 (black), on 16.01.2013 (blue), and on 17.01.2013 (green). (b) At the Paranal Observatory on 09.01.2013 (red), on 10.01.2013 (black), and on 11.01.2013 (blue). (c) At the Izaña Observatory on 08.06.2005 (red), on 09.06.2005 (black), and on 10.06.2005 (blue).

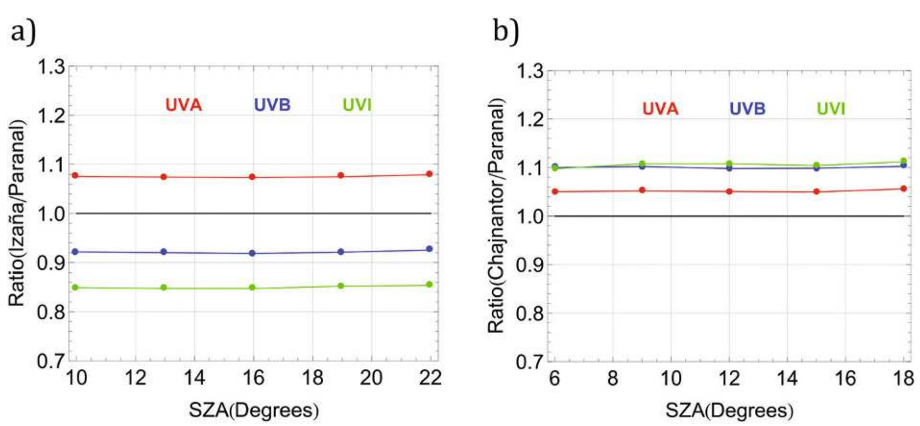

Fig. 2 (a) Ratio between UV integrals at the Izaña Observatory (on 09.06.2005) and at the Paranal Observatory (on 09.01.2013). UVA (red); UVB (blue); UVI (green). (b) Ratio between UV integrals on the Chajnantor Plateau (on 15.01.2013) and at the Paranal Observatory (on 09.01.2013). UVA (red); UVB (blue); UVI (green).

09.06.2005) and at the Paranal Observatory (on 09.01.2013). Fig. 2b shows the ratio between UV integrals on the Chajnantor Plateau (on 13.01.2013) and at the Paranal Observatory (on 09.01.2013). Fig. 2a and 2b do not significantly change when comparing UV levels corresponding to the different days in these measurement periods.

It can be observed in Fig. 2a that although the UVA irradiance measured at the Izaña Observatory is higher than at the Paranal Observatory, the opposite is true in the case of both UVB and UVI. As shown below, the difference in UVA values can be explained by the load of aerosols (greater in northern Chile) and by the albedo (higher in Tenerife). The difference in UVB and UVI values arises from the total ozone column (that as shown below is significantly lower in northern Chile).

Despite the fact that the total ozone column was roughly the same, it can be observed in Fig. 2b that all UV measurements are significantly higher on the Chajnantor Plateau than at the Paranal Observatory. As discussed below, most of the differences arise from the different altitudes (5100 m *vs.* 2635 m).

4. OMI-derived estimates of the UVI

The NASA EOS (Earth Observing System) OMI is one of the four instruments on the Aura satellite, launched on 15 July 2004 to a sun-synchronous near polar orbit. The OMI instrument is a nadir viewing UV spectrometer that is currently continuing the long-term ozone measurements by NASA's Total Ozone Mapping Spectrometer (TOMS) instrument. It measures the solar reflected and backscattered radiation in the wavelength range from 270 nm to 500 nm with a spectral resolution of 0.55 nm in the UV and 0.63 nm in the visible. These measurements are used to retrieve the total ozone column (the total column amount of ozone from the surface to the top of the atmosphere), aerosol and cloud cover characteristics, surface UV irradiance and gas traces. The instrument has a 2600 km wide viewing swath. The ground pixel size at the nadir position is 13 × 24 km (along × across track) for the total ozone column. It is capable of daily global mapping. We retrieved UVI data from the OMUVB product. OMI surface UV data are computed by means of an extension of the TOMS UV algorithm.[22] Firstly, the algorithm estimates the surface irradiance under cloud-free conditions using OMI total ozone and climatological surface albedo[50] as input parameters. Then, in order to determine the actual surface irradiance, the clear-sky irradiance is corrected with an OMI-based cloud modification factor (CMF) that accounts for the effect of clouds on UV radiation.[16] In this work, we used noontime OMI UVI gridded data. No correction for cloud changes between the satellite overpass time and local noontime is applied by the algorithm.

Fig. 3 shows the daily UVI retrieved from OMI over the period 2004–2012 (see blue line) as well as the corresponding monthly averages (see red line) on the Chajnantor Plateau (a); at the Paranal Observatory (b); and at the Izaña Observatory (c). As shown in Fig. 3a and 3b, annually over the period December–January, the OMI noontime UVI typically varies between 18 and 22 on the Chajnantor Plateau, and between 14 and 17 at the Paranal Observatory. As shown in Fig. 3c, the noontime UVI at the Izaña Observatory typically ranges from 10 to 14 annually over the period June–July. An important feature of the OMI UVI data is that its algorithm does not take into account the CMF when the altitude of the center of the satellite pixel is above 2500 m asl.[23] Therefore, OMI data shown in Fig. 3a are satellite UVI estimates computed under clear sky conditions.

When comparing ground-based measurements in Fig. 1 with UVI estimates retrieved from OMI, we found significant differences. In general terms a difference can be considered to be significant if it is greater than the standard uncertainty of the instrument (that in our case is about 5%). Under cloudless conditions, UVI peaked at 18 on the Chajnantor Plateau (on 15.01.2013); this value is 8% lower than the corresponding satellite-derived datum (19.5). In the case of the Paranal Observatory, UVI peaked at 16 on 09.01.2013, which roughly agrees with the corresponding OMI readings (16.6); note that the OMI value was marginally corrected for clouds (the clear-sky OMI UVI is 17.1 on 09.01.2013). Finally, in the case of the Izaña Observatory, UVI peaked at 13.5 on 09.01.2005; a value significantly greater (about 18%) than the corresponding OMI-derived UVI (11.4).

The significant differences detected between OMI-derived data and ground-based measurements were expected due to the complex surrounding topography in the case of the Chajnantor Plateau.[20] This problem should be negligible in the case of the Paranal (located on the top of a small hill surrounded by a somewhat homogeneous plateau). Moreover, although as discussed below most of the difference in the case of the Izaña Observatory arises from the changes in the local albedo through the day, the low resolution of OMI grid data (1 × 1 lat × lon) also contributes to the underestimation of ground data (the observatory is on the top of a mountain in the small Tenerife island, with a strong altitude gradient).

5. Analysis

5.1. Effect of albedo and aerosols

Fig. 2a shows that UVA measurements are greater at the Izaña Observatory than at the Paranal Observatory. As shown below, this is due to differences in the albedo and in the aerosol loading.

Differences in the albedo may arise from the fact that Izaña is often affected by the so-called sea of clouds phenomenon (*i.e.* by the presence of a dense cloud cover layer under the summit of the Observatory). Clouds under the summit might enhance the average albedo by 0.30, which can lead to increments in UV irradiance of up to 9%. *e.g.*[51] Due to the effect of a cloud layer below the station, the albedo at the Izaña Observatory can be about 0.35,[52] while the UV albedo at the Paranal Observatory was measured to be only 0.1.

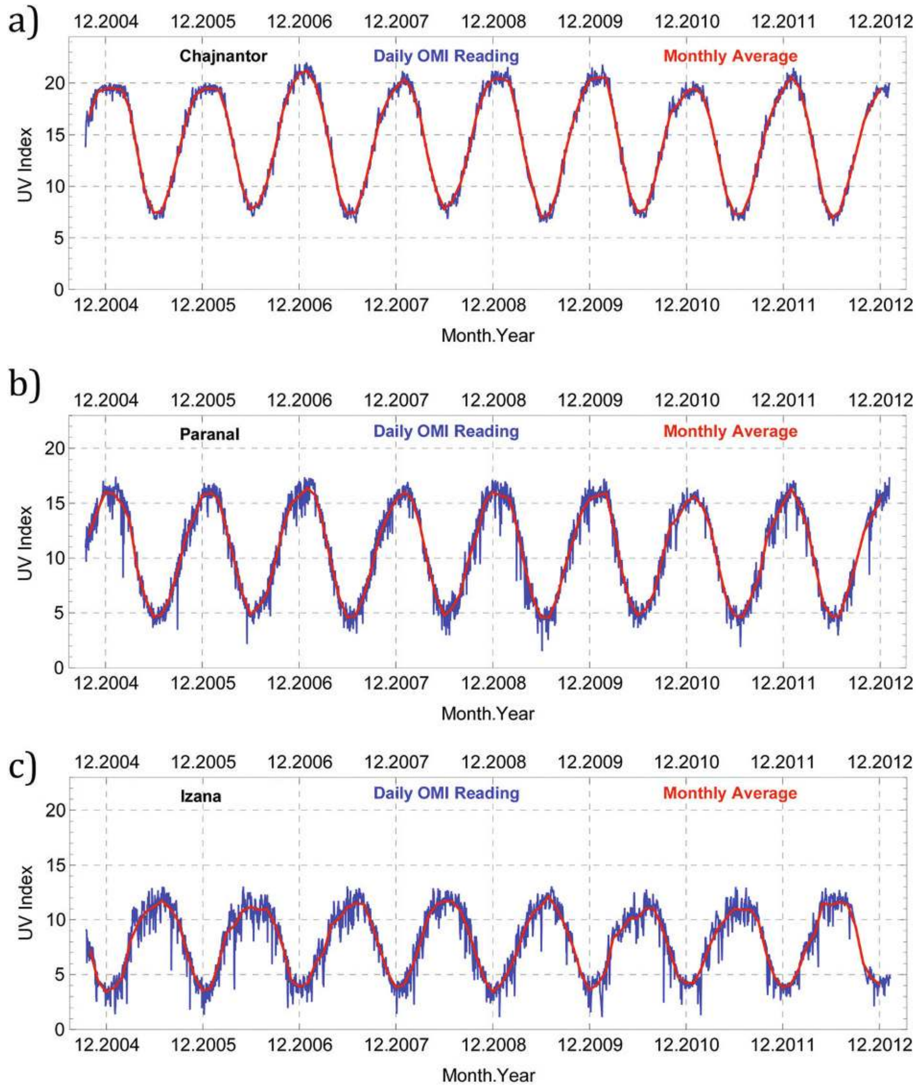

Fig. 3 Noontime UVI retrieved from OMI readings over the period 2004–2012. The number "12" in the abscissa tick labels means "December". The blue line stands for the daily estimates of UVI; the red line stands for monthly averages. (a) Chajnantor Plateau. (b) Paranal Observatory. (c) Izaña Observatory.

On the other hand, the parameters used to represent the aerosol influence are in the case of the Izaña Observatory fully available; this Observatory is a contributor of the Aerosol Robotic Network (AERONET),[32] a well-known network of ground-based remote sensing aerosols. However, in the case of the Atacama Desert no measurements of the properties of aerosol loading in the UV range have been reported.

Answering this challenge, we carried out spectral measurements of both the direct and the global irradiance at the Paranal Observatory around noon on 09.01.2013. Both the AOD and the single scattering albedo (SSA) were retrieved from these quality-controlled spectral measurements by applying the methods described by Cordero *et al.*[53] (in the case of the AOD); and by Bais *et al.*[54] and Buchard *et al.*[55] (in the case of the SSA). These methods are based on the comparison of the measured spectral irradiance with UV spectra computed by using a radiative transfer model. The retrieved values of the AOD and SSA are those leading to the best match between the measured and the computed spectra. As a radiative transfer model we used UVSPEC.[56] The selected radiative transfer solver was the pseudo-spherical version of the DISORT solver as described by Dahlback and Stamnes;[57] the extraterrestrial spectrum was quoted from Gueymard.[58] By using the methods described above, we estimated that the AOD and the SSA at the Paranal Observatory were on 09.01.2013 about 0.15 and 0.7, respectively. These values are significantly different from those at the Izaña Observatory on 09.06.2005 (AOD = 0.08 and SSA = 0.94).

We conclude that most of the differences in the UVA measurements shown in Fig. 2a can be explained by the load of aerosols (greater in northern Chile) and by the albedo (higher in Tenerife).

5.2. Effect of the ozone

Fig. 2a shows that the measurements of both the UVB and UVI are significantly higher at the Paranal Observatory than at the

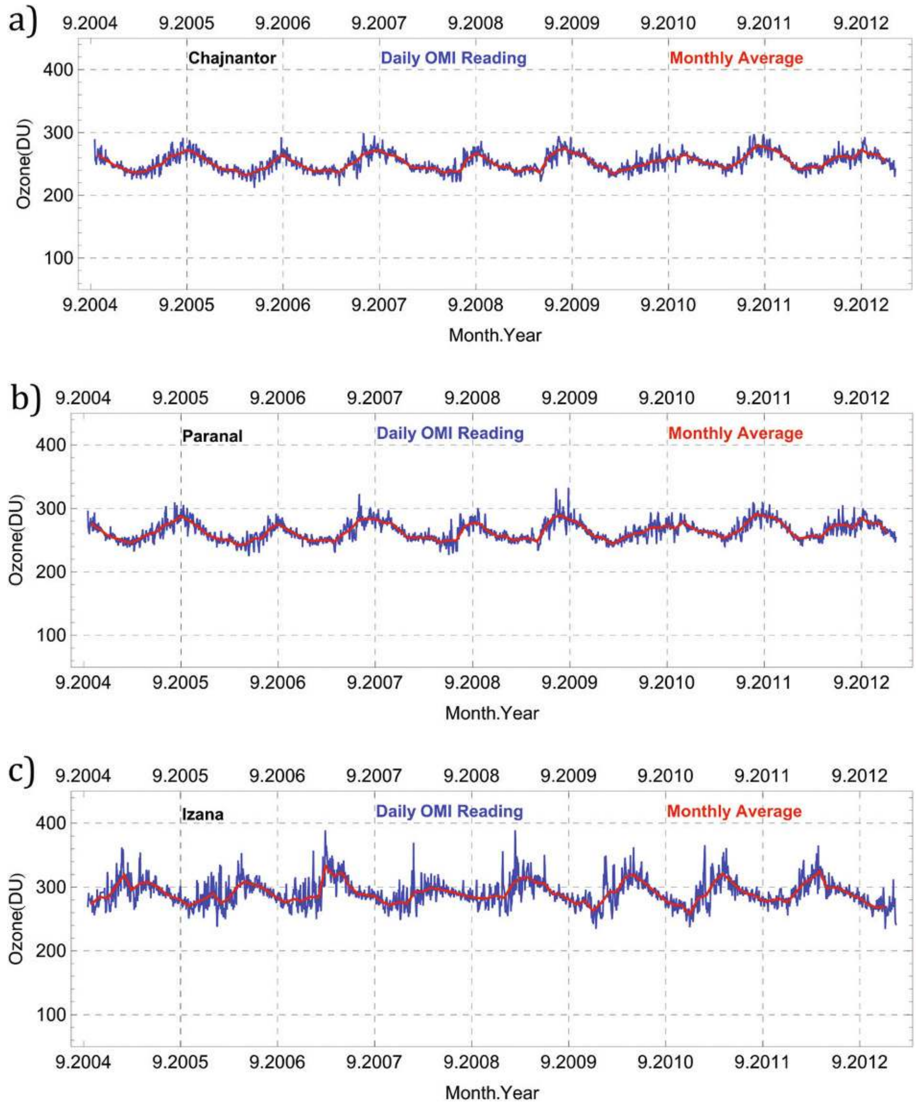

Fig. 4 OMI-derived estimates of the total ozone column over the period 2004–2012. The number "9" in the abscissa tick labels means "September". The blue line stands for the daily ozone estimate; the red line stands for monthly averages. (a) Chajnantor Plateau. (b) Paranal Observatory. (c) Izaña Observatory.

Izaña Observatory. As shown below, this difference is likely to arise from differences in the total ozone column.

Fig. 4 shows the OMI-derived total ozone column over the period 2004–2012 (see blue line) as well as the corresponding monthly averages (see red line) on the Chajnantor Plateau (a); at the Paranal Observatory (b); and at the Izaña Observatory (c). We obtained the total ozone column values from the OMTO3 product. Seasonal variations in the ozone values are apparent. Annually, monthly averages peak in spring. Moreover, peak ozone values are usually higher at the Izaña Observatory (see Fig. 4c) than on the Chajnantor Plateau (see Fig. 4a) and at the Paranal Observatory (see Fig. 4b).

As shown in Fig. 4a and 4b, over the period December–January, the ozone usually varies between 230 and 260 Dobson units (DU) on the Chajnantor Plateau, and between 250 and 280 DU at the Paranal Observatory. As depicted in Fig. 4c, the ozone at the Izaña Observatory ranges from 280 to 310 DU over the period June–July. The average of the OMI-derived total ozone column at the Izaña Observatory in June (301 DU) is typically about 18% higher than at the Paranal Observatory in January (255 DU), and 23% higher than on the Chajnantor Plateau in January (244 DU).

In order to quantify the strong effect of the ozone, we have computed the UVI by using the UVSPEC model under the conditions observed at the Paranal Observatory on 09.01.2013 (albedo = 0.1; AOD = 0.15; SSA = 0.7) but assuming different ozone amounts (see Fig. 5a). The data shown in Fig. 5a, and the different aerosol loading (see section 5.1), suggest that the differences in the UVI measurements (between Izaña and Paranal shown in Fig. 2a) can be explained by significant differences in the total ozone column.

The ozone column amounts at the Izaña Observatory on 09.06.2005 and at the Paranal Observatory on 09.01.2013 were retrieved from our ground-based spectral measurements of the

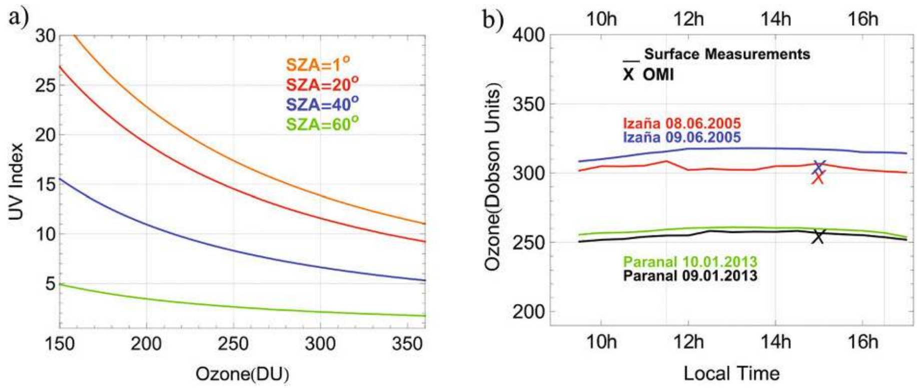

Fig. 5 (a) Change in the UVI with the total ozone column. The UVI was computed by using the UVSPEC model under the conditions observed at the Paranal Observatory on 09.01.2013 (albedo = 0.1; AOD = 0.15; SSA = 0.7; altitude = 2635 m) but assuming different solar zenith angles: 1° (orange line); 20° (red line); 40° (blue line); 60° (green line). (b) Total ozone column retrieved from ground-based measurements (see lines) and OMI estimates (see crosses) at the Paranal Observatory and at the Izaña Observatory. Color indicates the dates. Red: 08.06.2005, Izaña; blue: 09.06.2005, Izaña; black: 09.01.2013, Paranal; green: 10.01.2013, Paranal.

global irradiance by applying the method described by Stamnes *et al.*[59] This method is based on the comparison of measured global irradiance ratios at two wavelengths in the UV part of spectrum with a synthetic chart of this ratio computed for a variety of ozone values. One of the wavelengths should be appreciably absorbed by ozone compared with the other. Although several combinations are possible, our choices were 305 and 340 nm. When measurements are carried out under cloudless conditions, this retrieval method can be considered reliable (see Mayer *et al.*[60]).

Fig. 5b shows the total ozone column progression computed from our ground-based measurements at the Paranal Observatory and at the Izaña Observatory. The OMI-derived estimates of the TOC are also shown in Fig. 5b (see crosses). However, note that unfortunately in the case of Paranal, only the OMI estimate on 09.01.2013 is available due to gaps in the OMI time series. As shown in Fig. 5b, our ground-based measurements are in good agreement (±4%) with the ozone estimates retrieved from OMI. According to the data shown in Fig. 5b, the total ozone column at the Izaña Observatory was on 09.06.2005, about 60 DU higher than at the Paranal Observatory on 9.1.2013. This difference explains why both UVB and UVI are significantly higher at the Paranal Observatory than at the Izaña Observatory (as shown in Fig. 2a).

5.3. Effect of the altitude

Fig. 2b allows comparing the UV measurements on the Chajnantor Plateau (on 15.01.2013) and at the Paranal Observatory (on 09.01.2013). We selected these two particular days because according to our ground-based measurements, the total ozone column was approximately the same at both locations. As shown in Fig. 2b, all compared UV measurements are significantly greater on the Chajnantor Plateau than at the Paranal Observatory. This result was expected since the high altitude leads to a shorter path length through air (including ozone and possibly other absorbers and scatterers).[61]

In order to assess the effect of altitude, we have computed the UVI by using the UVSPEC model under the conditions observed around noon (SZA = 5°) at the Paranal Observatory on 09.01.2013 (AOD = 0.15; SSA = 0.7) but assuming different altitudes (see Fig. 6a). The data shown in Fig. 6a allow us to conclude that, under similar aerosol loading, UVI increases around 4% per km. This increment agrees with the differences in the UVI measurements (between Chajnantor and Paranal) shown in Fig. 2b. By comparing the UVI measurements in Fig. 2b, we conclude that in the Atacama Desert, the UVI increases around 4% per km in the range 2500–5000 m altitude. In the range 0–2500 m altitude, we expect a significantly higher increment per km, similar to those found elsewhere: 7% per km in the Himalayas;[19] 6.5% per km in Hawaii;[62] and 9% per km in the Alps.[63] Nevertheless, please note that local conditions are always complex and no general figures for the increase per km can therefore be derived.

It can be observed in Fig. 2b that although UVB measurements are 10% greater on the Chajnantor Plateau than at the Paranal Observatory, UVA measurements are only 5% greater. These wavelength dependent differences also arise from the different altitude; the blue line in Fig. 6b stands for the ratio between the spectra estimated at SZA = 5° from our ground-based measurements on the Chajnantor Plateau (on 15.01.2013) and at the Paranal Observatory (on 09.01.2013). Red crosses in Fig. 6b stand for the ratio between spectra computed by using the UVSPEC model at SZA = 5° assuming the same aerosol conditions but different altitudes (5100 m and 2635 m). The good agreement shown in Fig. 6b allows us to conclude that the differences observed in surface UV on the Chajnantor Plateau and at the Paranal Observatory are mostly due to the different altitudes (*i.e.* the reduction in the atmospheric column). The role of the aerosol loading was surprisingly slight. Although the aerosol loading on the Chajnantor Plateau is expected to be significantly lower than at the Paranal Observatory, the surrounding mountains constrain the

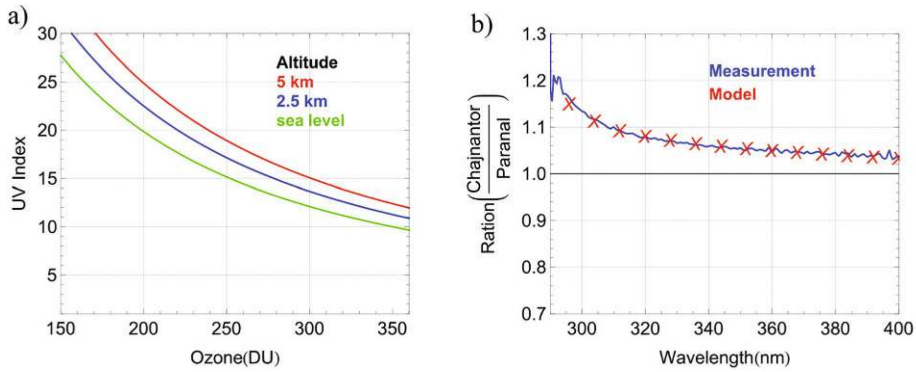

Fig. 6 (a) Change in the UVI with the altitude. The UVI was computed using the UVSPEC model under the conditions observed around noon (SZA = 5°) at the Paranal Observatory on 09.01.2013 (albedo = 0.1; AOD = 0.15; SSA = 0.7) but assuming different altitudes: 5 km (red line); 2.5 km (blue line); 0 km (green line). (b) Blue line stands for the ratio between spectra estimated at SZA = 5° from our ground-based measurements on the Chajnantor Plateau (on 15.01.2013) and at the Paranal Observatory (on 09.01.2013). Red crosses stand for the ratio between spectra computed by using the UVSPEC model at SZA = 5° and at different altitudes (5100 m and 2635 m).

dispersion of the dust (the surface is semi-arid) linked with the ongoing building of an Observatory on the plateau.

5.4. Effect of clouds

In addition to the cloud-linked albedo effect (if the measurement station is above the clouds) described in section 5.1, broken cloud conditions can also significantly enhance peak UV. Fig. 1a shows that the UVI peaked at 20 on the Chajnantor Plateau at 13:45 LT on 13.01.2013 (broken cloud conditions). This value is significantly greater than peak UV levels registered at the same location during the rest of the campaign. For example, on 15.01.2013 the UVI peaked at 18 at 13:45 LT (clear conditions). The difference of more than 10% between UVI levels registered at 13:45 LT on 13.01.2013 and at 13:45 LT on 15.01.2013, diminishes to only 3.5% when comparing UVI values registered on the same days but at 14:15 LT.

Fig. 7 shows the ratio between pairs of the spectra measured on the Chajnantor Plateau on 13.01.2013 and on 15.01.2013. It can be observed in this figure that spectra sampled at 14:15 LT (see blue line) agree in the UVA part of the spectrum but differences are apparent in the UVB part. These latter differences are due to the ozone; the total ozone column (retrieved from our ground-based measurements) on 13.01.2013 was lower than the concentration measured on 15.01.2013. However, the detected difference in the ozone is not large enough to explain the differences in the peak UV levels. In the case of the spectra sampled at 13:45 LT (see red line) the differences in both the UVA and UVB ranges are considerably greater. The UV irradiances measured at 13:45 LT on 13.01.2013 were indeed significantly higher than those measured during the rest of the campaign. We argue that the significant temporal variations can only be explained by the influence of clouds.

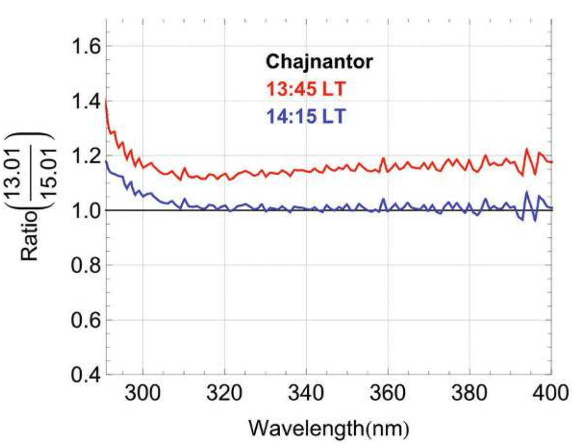

Fig. 7 Ratio between pairs of the spectra measured on the Chajnantor Plateau on 13.01.2013 and on 15.01.2013. Color indicates the time. Red line: spectra sampled at 13:45 LT; blue line: spectra sampled at 14:15 LT.

Clouds generally reduce surface UV irradiances. However, as observed around noon on 13.01.2013 on the Chajnantor Plateau, UV irradiance becomes higher than for clear sky, due to the broken cloud conditions. This cloud-linked enhancement in surface UV occurs when both direct sunlight and light scattered by clouds (*e.g.* the sides of bright broken clouds) reaches the detector. The effect has been extensively reported.[14–17] Indeed, NH's highest levels of surface UV, registered in Mauna Loa, Hawaii (3400 m altitude, 19°30′N)[18] and in Tibet (5000 m altitude, 29°N),[19] were measured under broken cloud conditions. In these high altitude cases, authors reported significant cloud-linked enhancements in local UVI that occasionally exceeded 20. Note also that Fig. 7 suggests that the cloud-linked enhancement increases with the wavelength.

5.5. Consistency check

Fig. 8a shows the ratio between the clear-sky model values of UV at the Izaña Observatory and at the Paranal Observatory. Fig. 8b shows the ratio between the clear-sky model values of UV on the Chajnantor Plateau and at the Paranal Observatory. These values were computed using the UVSPEC model under the conditions observed at the Paranal Observatory on 09.01.2013 (albedo = 0.1; AOD = 0.15; SSA = 0.7; altitude = 2635 m; ozone = 260 DU); at the Izaña Observatory on 09.06.2005 (albedo = 0.35; AOD = 0.08; SSA = 0.94; altitude = 2367 m; ozone = 320 DU), and on the Chajnantor Plateau on 15.01.2013 (albedo = 0.1; AOD = 0.15; SSA = 0.7;

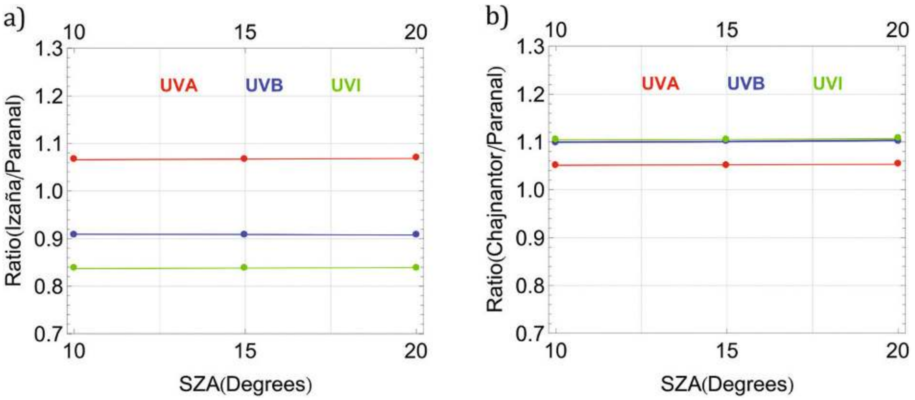

Fig. 8 (a) Ratio between modeled UV data at the Izaña Observatory and at the Paranal Observatory. UVA (red line); UVB (blue); UVI (green line). (b) Ratio between modeled UV data on the Chajnantor Plateau and at the Paranal Observatory. UVA (red line); UVB (blue); UVI (green line).

altitude = 5100 m; ozone = 260 DU). The agreement between measurements (see Fig. 2a and 2b), and modeled data (see Fig. 8a and 8b), confirms the consistency of our analysis.

6. Summary and conclusions

We report on the first quality-controlled spectral UV measurements in Chile's northern Atacama Desert carried out in January 2013 on the Chajnantor Plateau and at the Paranal Observatory by using a double monochromator-based spectroradiometer. The locations were selected because of their high altitude, prevalent cloudless conditions, and relatively low total ozone column. The measurements were aimed at confirming peak UV levels. Spectral measurements carried out at the Izaña Observatory were used for further comparisons.

The peak UVI at the Paranal Observatory was found to be about 15% higher than at the Izaña Observatory. This difference is mostly due to the ozone; the total ozone column at the Izaña Observatory is, in June, about 55–60 DU higher than it was at the Paranal Observatory in January. Additional differences in the UVA can be explained by the load of aerosols (greater in northern Chile) and by the albedo (often higher in Tenerife due to the "sea of clouds" phenomenon).

Due to the differences in altitude (5100 m *vs.* 2635 m), the peak UVI on the Chajnantor Plateau was found to be about 10% higher than at the Paranal Observatory under cloudless conditions. However, further enhancements of about 10% in the peak UVI were observed on the Chajnantor Plateau under broken cloud conditions.

The UVI peaked at 20 on the Chajnantor Plateau (on 13.01.2013, broken cloud conditions), 16 at the Paranal Observatory (on 09.01.2013, cloudless conditions), and 13.5 at the Izaña Observatory (on 08.06.2005, cloudless conditions).

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