



Record solar UV irradiance in the tropical Andes

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High elevation, thin ozone layer, and clear sky produce intense ultraviolet (UV) radiation in the tropical Andes. Recent models suggest that tropical stratospheric ozone will slightly decrease in the coming decades, potentially resulting in more UV anomalies. Data collected between 4300 and 5916 m above sea level (asl) in Bolivia show how this trend could dramatically impact surface solar irradiance. During 61 days, two Eldonet dosimeters recorded extreme UV-B irradiance equivalent to a UV index (UVI) of 43.3, which is the highest ground value ever reported. If they become more common, events of this magnitude may have societal and ecological implications, which make understanding the process leading to their generation critical. Our data show that this event and other major UV spikes were consistent with rising UV-B/UV-A ratios in the days to hours preceding the spikes, trajectories of negative ozone anomalies (NOAs), and radiative transfer modeling.

Keywords: record solar UV irradiance, negative ozone anomaly, UV index

INTRODUCTION

In the past decades, stratospheric ozone loss attributed to man-made chlorofluorocarbons has led to the penetration of increasing amounts of UV-B in the atmosphere, raising concern about the levels of biologically-damaging radiation reaching the ground. However, assessing the role of ozone fluctuations in UV trends is often challenged by limited conditions of atmospheric clarity (Herman and Keating, 2008; NOAA, 2008; Lee-Taylor et al., 2010; WMO, 2011).

Column ozone is naturally thinner over the tropics, and UV increases with elevation, clear skies, and low aerosols (Blumthaler et al., 1997). As a result, the tropical Andes represent a particularly valuable study area for quantifying the amount of biologically damaging radiation (UV-A, UV-B) reaching the ground (Piazena, 1996), and its wavelength dependence on ozone in a naturally occurring extreme environment.

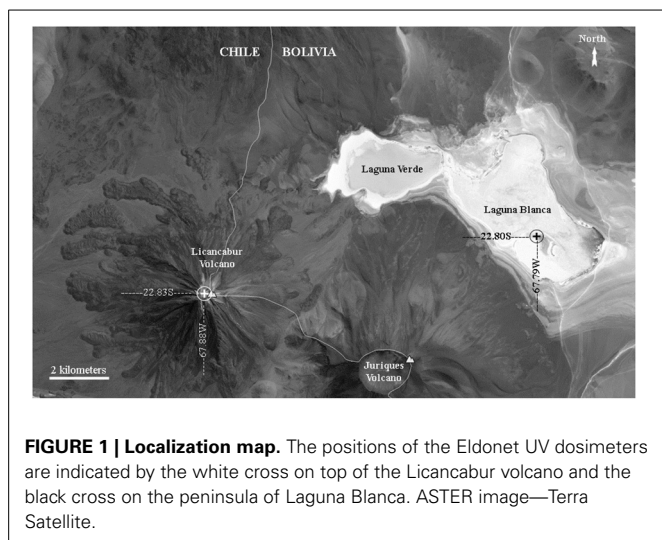
The Andes form the highest mountain range outside Asia with over 100 peaks above 6000 m asl. They have an extreme aridity index between 18 and 28°S with no residual glaciers even above 6700 m (Bradley et al., 2006).

Between 2003 and 2004, two European Light Dosimeter Network (Eldonet) dosimeters (Häder and Lebert, 2006) were deployed in Bolivia near the Tropic of Capricorn at the summit of Licanabur (22.48°S/67.47°W, 5917 m asl) and at Laguna Blanca (22.50°S/67.53°W, 4340 m asl) (Figure 1) to monitor PAR (400–700 nm), UV-A (315–400 nm), and UV-B (280–315 nm) (Cabrol et al., 2009). The data collected during this survey revealed extreme UV-B irradiance. The following sections describe data results, modeling, and envision plausible causes for what are the highest UV-B irradiance values (and resulting UV Index) ever recorded on Earth to date.

INSTRUMENTS AND DATA

Eldonets are proven dosimeters that have been functional since 1999 as part of an international network of UV and visible radiation monitoring in the three biologically-relevant wavelength bands used in this study. The network is based on more than 100 stations distributed over five continents, allowing measurement of the latitudinal and longitudinal light climate distribution. In addition to the European sites, several instruments are active in South America (including those of the present study), New Zealand, India, Africa, and China. The absolute calibration of the instruments was tested in an intercomparison of several radiometers in Garmisch-Partenkirchen (Southern Germany) (Häder et al., 1999). Another international intercomparison took place 2006 at the Physikalisch-Meteorologisches Observatorium in Davos, Switzerland). The absolute spectral irradiance is traceable to the primary irradiance standard of the Physikalisch-Technische Bundesanstalt (PTB, Braunschweig, Germany, through the transfer standards F34, F324, F364, and F376. For the Eldonet instrument participating in the test a calibration coefficient C of 1.0044 has been calculated (certificate number 2006/BB14/1).

Challenging environmental conditions in the high Andes resulted in ~35% data loss, but recovered data were consistent between sites and over time. In average ozone conditions (250 Dobson Units, DU) UV-B maxima were 1.3 W/m² in winter and 4.1 W/m² in summer. The instruments also recorded significantly higher values between November 25, 2003 and January 25, 2004. Correlated values of UVI reached 20–29 in eight instances, consistent with observations recently published for Mediterranean sites. Jacovides et al. (2009) UVI peaked at 43.3 on December 29, 2003, and reached 31.7, 29.8, and 32.6 on January 10, 15, and 17,



respectively. These are the highest values ever recorded anywhere on Earth. Each major event was preceded by several days of rising UV-B/UV-A ratio, with the highest value (0.129) recorded on December 29, 2003 (**Figure 2A**). While all UVI events >29 were observed at Licancabur, similar UV patterns with somewhat lower UVI were observed at Laguna Blanca 10 km away.

Additional data collected through November 2004 at Laguna Blanca further showed 53 days of maximum UV-B/UV-A ratio exceeding 0.05, 15 days over 0.06, and two over 0.08. The highest value was reached on January 25, 2004, with UVI = 26.2.

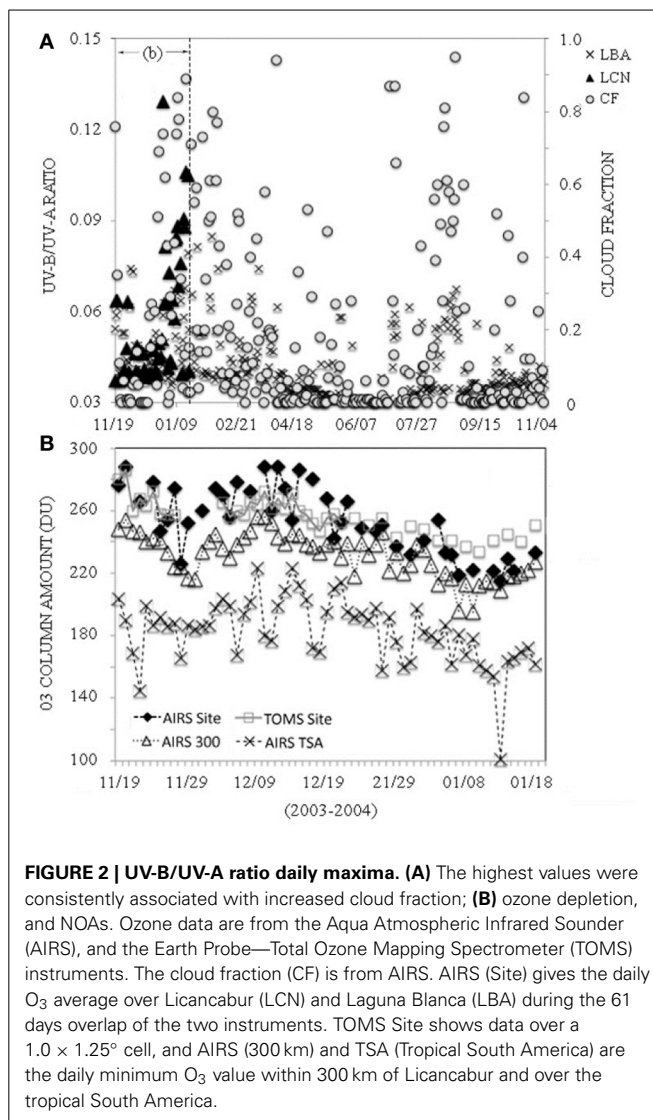
When trying to identify the causes of these events, repetitive patterns were found, including increasing UV-B/UV-A ratios in the days to hours preceding the spikes, decreasing column ozone amount (**Figure 2B**), and the presence of NOAs.

The relationship between the concentration of ozone layer in the stratosphere and increase the UV radiant flux levels (mainly the UV-B, 280–315 nm) reaching the Earth's surface—including strong hourly to daily variations in the UV-B/UV-A ratio—has long been established (e.g., McKenzie et al., 1991; Madronich et al., 1995; Siani et al., 2002; Kudish et al., 2005; Kazadzis et al., 2009), and their ecological and societal impact are continuously being reassessed (e.g., Kerr et al., 2002).

Here, ratios over 0.05 were also regularly associated with the intermittent presence of cumulus clouds leading to high diurnal UV variability, particularly during the wet season (November–March), and later in the year, during winter storms at Laguna Negra (**Figure 2A**).

MODELING APPROACH

Measured UV values were compared with clear-sky radiative transfer model calculations. Spectral UV irradiance reaching the ground with clear sky was simulated by the radiative transfer model LibRadtran (Mayer and Kylling, 2005; Mayer et al., 2008) with 16 streams and a tropical standard atmosphere with ground-surface pressure values at the respective elevations above sea level. Resulting spectral transmission was scaled to spectral irradiance in $W\ m^{-2}\ nm^{-1}$ using a high-resolution extraterrestrial solar spectrum (Kurucz, 1992). Other input values included a 0.97



aerosol single scattering albedo and a 0.71 asymmetry parameter that are typical for continental conditions (Hess et al., 1998). A rural aerosol profile was assumed to be valid with background aerosol values above 2000 m. The aerosol profile was scaled to a very small aerosol optical depth of 0.032 at 340 nm. Ozone absorption cross sections were taken from Bass and Paur (1985). A constant water vapor column amount of 3 kg/m² typical for dry atmospheric conditions was applied, which is close to satellite-based MODIS data¹. Values of spectral surface albedo were selected for gravel and loam at all elevations (Feister and Grewe, 1995). Spectral irradiances calculated at wavelength steps of 1 nm covered 280–700 nm and were convoluted with a triangular slit function having a full bandwidth of 1 nm. Spectral irradiance was integrated within the 280–315 nm, 315–400 nm, and 400–700 nm ranges. Erythemal effective irradiance was calculated by weighting

¹<http://lance-modis.eosdis.nasa.gov/cgi-bin/imagery/firemaps.cgi> [Accessed].

spectral irradiance data with the erythemal action spectrum by CIE (McKinlay and Diffey, 1987).

THE JANUARY 17, 2004 CASE

Figure 3 illustrates the January 17, 2004 case. UV-A increased in the morning to values that reached or exceeded clear-sky irradiance for a few minutes, possibly partly due to cloud edge scattering as satellite imagery shows a high-reaching cloud field passing the site from the northwest. UV-B and UV-A may have been, thus, temporarily enhanced by cloud scattering. Comparatively, UV-B showed a substantially higher relative increase that lasted for over 2 h. Measured UV-B was then 2.4-fold that of clear-sky irradiance at a typical column ozone value of 240 DU. It peaked at $\sim 8.15 \text{ W m}^{-2}$, exceeding modeled clear-sky of UV-B = 6.4 W m^{-2} , UVI = 66 for a modeled column ozone of 75 DU at 14:30 UTC (SZA = 30.5°). Peak height and duration could not, thus, be only explained by radiation scattered from cloud edges. Values dropped for 2 h as the clouds passed, then UV-A increased again. UV-B remained below 1 W m^{-2} , which is explained if scattering with optically thick clouds enhanced the absorption by tropospheric ozone, thereby contributing to the pronounced drop in UV-B and reduced UV-B/UV-A ratios (Feister et al., 2011).

Common to all extreme cases was also the rapid east to west air flow in the middle to upper stratosphere. The sources and paths of air parcels reaching Licancabur during those events were determined using the Deutscher Wetterdienst (DWD) trajectory model for tropospheric and stratospheric pressure levels up to 7 days prior to each of the UV-B peak events (**Figures 4A–D**). The model is based on archived three-dimensional pressure and wind fields derived by the DWD global model GME (Kottmeier and Fay, 1998; Fay et al., 2004), and was applied to 14 atmospheric pressure levels between the middle troposphere at 500 hPa (5.5 km) and the middle stratosphere at 5 hPa (36 km).

On January 10, 2004, air parcels at 5 hPa originated from the subtropical/tropical eastern Indian Ocean and reached Licancabur within 7 days. During the same period, lower tropospheric air masses started over the hot and humid Amazon rainforest, and were forced up- and downward several times between 3 and 14 km in the middle and upper troposphere when passing over the high Andes ($\geq 5000 \text{ m asl}$). Air parcels between 100 and 80 hPa (16.5–18 km) moved with speed up to 190 km/h from the Central Tropical Pacific ($9^\circ\text{S}/110^\circ\text{W}$), slowed down to $\sim 20 \text{ km/h}$ to finally start an anti-clockwise circular motion as they approached South America. They were forced up by the Andes further east, passed over Licancabur on January 12, moved westward before returning east over the site on January 17, 2004 at 9:00 am. Trajectories at higher elevations of 80–90 hPa were comparable although somewhat shifted south. They showed air parcels lifted upward once and reaching higher elevations up to 17.6 km altitude, possibly entering the lower stratosphere.

Differing from the upper troposphere, lower stratosphere trajectories between 60 and 65 hPa (19.5–21 km) showed meridional paths. They started 500 km off the Antarctic coast in the Southern Pacific ($70^\circ\text{S}/120\text{--}140^\circ\text{W}$) at 95 and 115 hPa. Although the ozone hole was well developed in the 2003 southern spring, ozone had risen back to 250–275 DU (TOMS) by January 2004. Transport of ozone-poor air from Antarctica at that time of the year is unlikely.

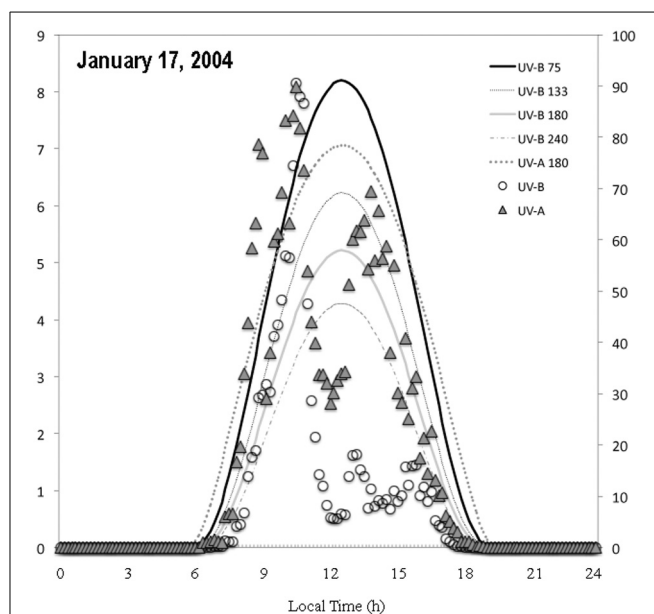


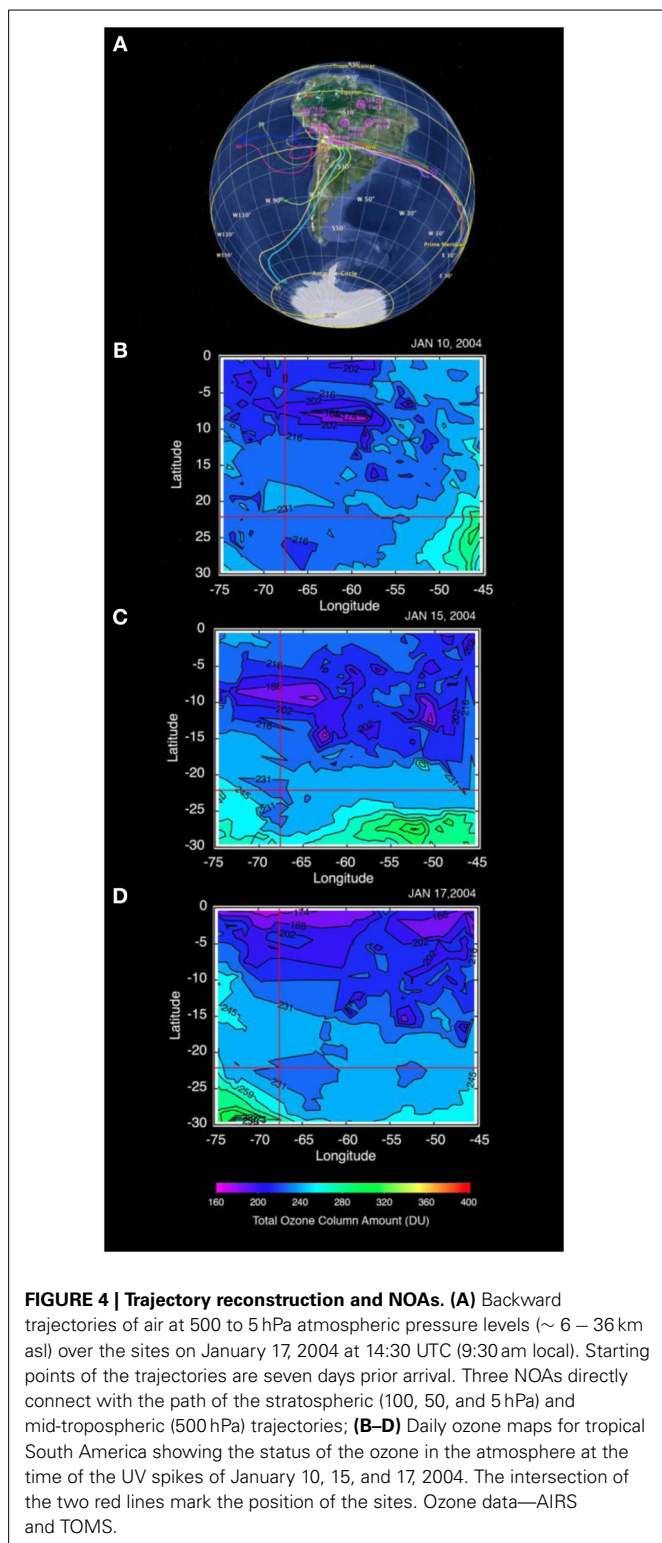
FIGURE 3 | UV irradiance at Licancabur. Measured UV-A and UV-B on January 17, 2004 at Licancabur compared to results of clear-sky model calculations using LibRadtran with column ozone of 75 DU, 133 DU, 180 DU, and 240 DU (lines).

However, it is worth noting that the air reaching Licancabur originated in the Antarctic stratosphere. Its composition of trace gases (e.g., $\text{ClO}_{(x)}$, $\text{BrO}_{(x)}$), particularly those with medium to long lifetimes could have been transferred to the tropical Andes (Montzka and Reimann, 2011).

DISCUSSION AND CONCLUSIONS

Overall, the regional satellite observations and trajectory modeling are consistent with the *in situ* measurements of record solar irradiance. Converging lines of evidence include: (a) both ozone depletion, and the number and amplitude of NOAs strongly increased over the tropical South America between December 29, 2003 and January 17, 2004 with measured daily UV-B/UV-A ratio maxima increasing accordingly. Although no NOA below 150 DU was observed in the orbital datasets directly over Licancabur, this may only reflect the limitation of orbital daily data, which only provide an average snapshot of atmospheric events. NOAs between 101 and 150 DU were present in the tropical Andes in a timeframe compatible with the observed UV spikes; (b) some of the NOAs connected to the path of the mid-stratospheric air current carrying ozone-poor air, and to that of the mid-tropospheric 500 hPa air parcel trajectory from the north. Those, too, may have contributed to the spikes; and (c) two instruments spatially separated by 10 km showed consistent data (**Figure 5**).

While trajectories show horizontal and vertical traces of air parcels, they cannot reveal changes in ozone concentration due to dynamics and photochemistry along their travel paths. Deep convection in high-reaching clouds, particularly forced uplifting of tropospheric air approaching high mountain ranges, can lead to overshooting of tropospheric air into the lower stratosphere



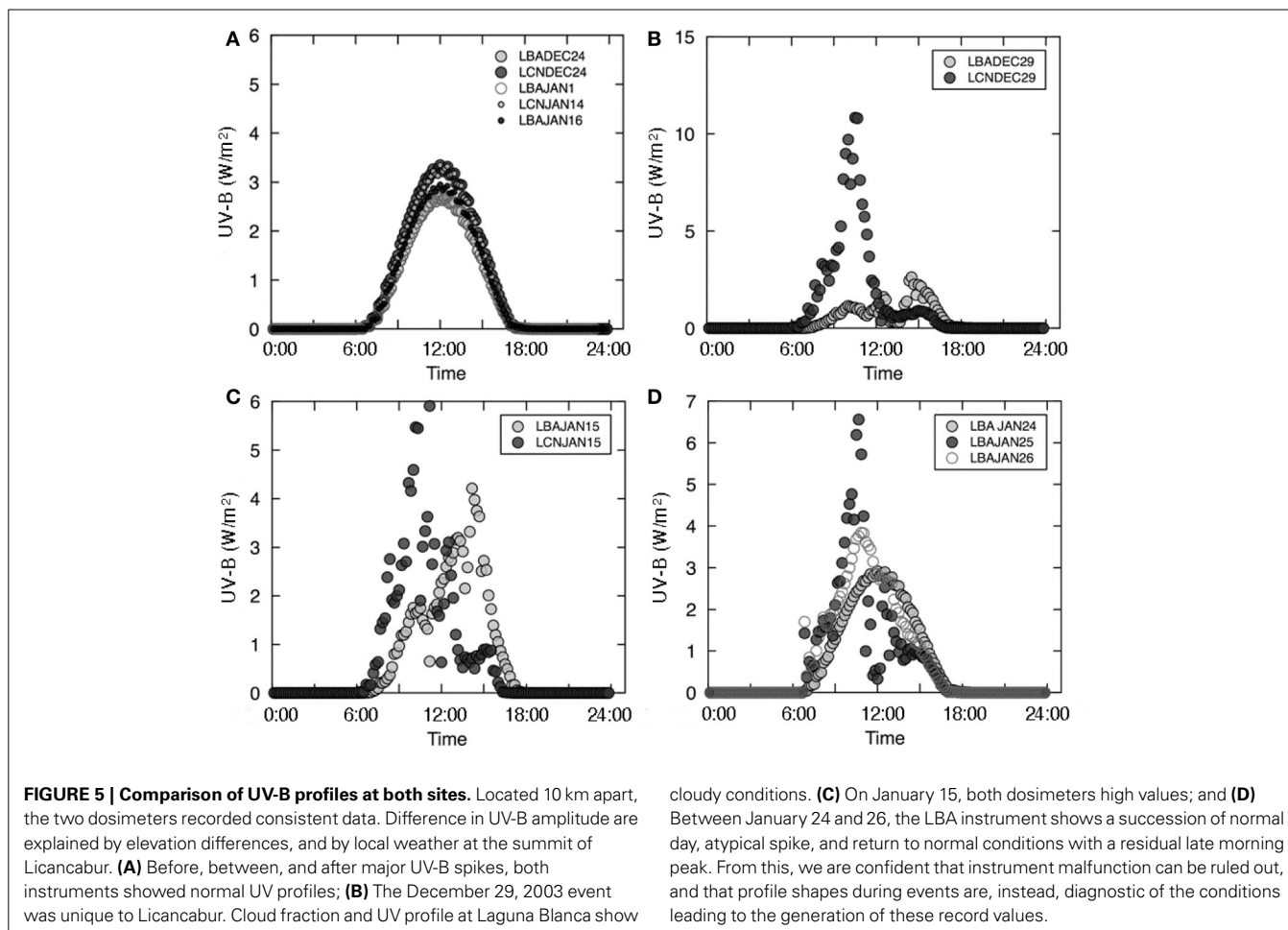
by crossing the high and cold tropopause. This air may contain ozone-destroying gases such as bromine compounds and nitrogen species (Gettelman et al., 2009), and may contribute to NOA formation and intensification.

Deep convection and high peaks in the Andes have also been shown to trigger gravity waves that propagate upwards into the stratosphere and create convectively unstable conditions between 23 and 35 km altitude (Spiga et al., 2008). Wave-breaking or dissipation provides a drag force directly over the topography. Mountain waves with shorter horizontal wavelengths show a westward propagation direction in compliance with NOA movement, longer vertical wavelengths, and larger momentum fluxes than waves further south and downstream of the mountains (Alexander and Teitelbaum, 2011). Due to decreasing air pressure with height, waves grow in strength, leading to changes in temperature and circulation, thus affecting ozone transport in the Brewer Dobson circulation. A wave-generated temperature decrease in the lower to mid-stratosphere would also tend to decrease ozone by enhancing photochemical ozone loss.

Other contributing factors may also include elevated levels of water transported from the troposphere into the stratosphere at very low temperatures in January (<200 K) (Voemel et al., 2002). They can swell and dilute sulfate aerosols, and increase the rate of heterogeneous activation of chlorine from chlorine reservoirs such as ClONO₂ and HCl, thus accelerating ozone destruction (Anderson et al., 2012). MODIS Aqua and Terra satellite data collected by the Fire Information for Resource Management System (FIRMS, 2013) show abundant fire locations west and north of Licancabur in the week preceding January 17, 2004. From those, additional particulate sulfate aerosol and sulfur compounds such as OCS, SO₂, and SO₄²⁻ may have been transported and uplifted, further contributing to the ozone loss (Rasch et al., 2008; Bruehl et al., 2012).

Finally, although the evidence is circumstantial, an X45 class solar flare also took place on November 4, 2003, becoming the largest event ever recorded with instruments (Thomson et al., 2004). Heightened solar activity lasted over 5 months with additional events in the X10-17.2 class range between October 2003 and March 2004. Solar particle events have been shown to affect atmospheric chemistry (NO_y and HO_x) and foster ozone depletion (Woods et al., 2004). Our instruments were deployed 2 weeks after the X45 flares and showed the most extreme UV variability between the time of their deployment and the end of March 2004. The coincidental timing of the historical solar activity with seasonal UV maximum, and weather pattern that brings atmospheric instability over the Andes may have been additional factors that could have contributed to the generation of these unprecedented record UVI values.

Solar UV radiation is a major stress factor for the biota compromising the health of humans, terrestrial and aquatic ecosystems. Short-wavelength UV-B radiation damages DNA, affects photosynthesis, and decreases viability in eggs and larval stages of terrestrial and aquatic animals (Häder et al., 2011). Even though the high Andes are only sparsely populated by humans, their health can be affected by these record UV-B episodes. Therefore it is paramount that systematic monitoring in these wavelengths be undertaken including at lower elevations to understand the nature, extent, and significance of these high UV-B radiation events for human health and activity as well as for ecosystems.



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