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Extreme ultraviolet index due to broken clouds at a midlatitude site, Granada (southeastern Spain)

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ABSTRACT

Cloud cover usually attenuates the ultraviolet (UV) solar radiation but, under certain sky conditions, the clouds may produce an enhancement effect increasing the UV levels at surface. The main objective of this paper is to analyze an extreme UV enhancement episode recorded on 16 June 2009 at Granada (southeastern Spain). This phenomenon was characterized by a quick and intense increase in surface UV radiation under broken cloud fields (5–7 oktas) in which the Sun was surrounded by cumulus clouds (confirmed with sky images). Thus, the UV index (UVI) showed an enhancement of a factor 4 in the course of only 30 min around midday, varying from 2.6 to 10.4 (higher than the corresponding clear-sky UVI value). Additionally, the UVI presented values higher than 10 (extreme erythemal risk) for about 20 min running, with a maximum value around 11.5. The use of an empirical model and the total ozone column (TOC) derived from the Global Ozone Monitoring Experiment (GOME) for the period 1995–2011 showed that the value of UVI ~ 11.5 is substantially larger than the highest index that could origin the natural TOC variations over Granada. Finally, the UV erythemal dose accumulated during the period of 20 min with the extreme UVI values under broken cloud fields was 350 J/m^2 which surpass the energy required to produce sunburn of the most human skin types.

1. Introduction

Despite the solar ultraviolet (UV) radiation (100–400 nm) represents only the 8% of the whole solar spectrum at the top of the atmosphere (Iqbal, 1983), these high energetic wavelengths affects many biological, ecological and photochemical processes, being often harmful for living organisms. For instance, Diffey (1991) reported that UV radiation may cause substantial adverse effects on plant growth, photosynthesis and aquatic ecosystems. Additionally, a long-term over-exposure to UV radiation can have detrimental consequences on human health (skin cancer, cataracts, or immunological impacts). The last annual report the American Cancer Society (ACS) (ACS, 2011) informed that the incidence rates of melanoma (the most dangerous type of skin cancer) have been increasing for at least 30 years in USA (incidence rates have increased by ~3% per year since 1992). Therefore there is a great interest in the analysis of UV radiation values at different regions worldwide.

Complex processes of scattering and absorption control the transmission of UV radiation through the atmosphere, causing a strong reduction in the UV at the Earth's surface. The stratospheric ozone is the main attenuating factor, being its influence highly wavelength-dependent since the ozone absorption increases as wavelength decreases (Bais et al., 1993). This effect is particularly intense for the UV erythemal irradiance (UVER), obtained weighing the solar UV radiation with the erythemal spectral response (McKinlay and Diffey, 1987), which can be estimated as 10.3 W/m^2 at the top of the

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atmosphere (Antón et al., 2009), and decreases to maximum values at surface of about 0.25 W/m^2 during summer at middlatitudes (e.g., Martínez-Lozano et al., 2002; Marín et al., 2005; Antón et al., 2009, 2011a).

The short-term variability of the UV radiation reaching the Earth's surface is mainly controlled by changes in the cloud cover (Alados-Arboledas et al., 2003; Calbó et al., 2005). Thus, cloudiness variability often masks the effects of ozone changes, and it may reduce, cancel or even reverse the expected UV increase related to the reduction in ozone amount (Glandorf et al., 2005). Cloud cover mainly has an attenuating effect in the UV waveband which ranges between 20% and 70% for overcast skies, depending on the cloud type, optical depth, and solar elevation angle (Calbó et al., 2005). Additionally, clouds may also have an enhancement effect, manifested by increased UV irradiance at the surface compared with the equivalent cloud-free situation. The magnitude of UV enhancements is not well established, being highly variable Thus, these enhancements can reach values of up to 30% over clear-sky values during several minutes in a row, pointing out the importance of these events (Estupiñan et al., 1996; Sabburg and Wong, 2000; Krzyscin et al., 2003; Parisi and Downs, 2004; Sabburg and Calbó, 2009). The enhancements were found to be most pronounced for large cloud cover of 5 to 7 oktas when the solar disk is unoccluded (Cede et al., 2002), being smaller in the UV band than in the visible and infrared intervals (Pfister et al., 2003). It is well documented that these short-term enhancements in UV levels may affect the photosynthesis rate of vegetation like marine algae or phytoplankton (Dromgoole, 1988; Gwynn-Jones, 2001). Additionally, the quick and intense UV increase could have detrimental consequences for human skin and eyes, although the literature about the health effects of these episodes is quite scarce.

This paper focuses on the analysis of an extreme UV enhancement episode associated with broken cloud fields which occurred on 16 June 2009 at Granada (southeastern Spain). The variable used in this study is the UV index (UVI) which has become a useful vehicle to inform the public about the potentially harmful effects of the UV radiation (WMO, 1998).

2. Instruments and data

A broadband UV pyranometer, model UVB-1, manufactured by Yankee Environmental Systems, Inc. (Massachusetts, US), is installed since 2005 on the rooftop of the Andalusian Center for Environmental Studies (CEAMA, 37.17° N, 3.61° W, 680 m a.s.l.) at Granada, southeastern Spain. Measurements were sampled every 10 s and recorded as one minute mean voltages on Campbell CR10X data acquisition system. These output voltages are converted into UVER data by means of the calibration factors derived from the calibration and intercomparison campaign of broadband UV radiometers held in the observatory "El Arenosillo" (Spain) in September 2007 and June 2011. These campaigns included the spectral and angular characterization of all instruments and their absolute calibration, performed through the outdoor intercomparison with respect to a reference Brewer spectroradiometer and the QASUME unit from the Physikalisch-Meteorologisches Observatorium Davos/World Radiation Center (PMOD/WRC) (Vilaplana et al., 2009). Once obtained the UVER values, the UV index is calculated by multiplying these values (expressed in W/m^2) by 40 according to the joint recommendation of the WMO, WHO, UNEP and ICNIRP Meeting on UV-B radiation and UV forecast (WMO, 1998). Antón et al. (2011a) compared the UVI data provided by the UVB-1 pyranometer installed at Granada with simulations from the libRadtran radiative transfer code for the period 2006–2009, reporting mean relative differences around 5% which indicates the high reliability of the UVER data used in this paper.

An All-Sky Imager provides images of the whole sky dome in daytime at 5-min intervals, being commonly used for atmospheric radiative transfer studies (Cazorla et al., 2008, 2009). This instrument is located close to the UVB-1 pyranometer, and thus their images were critical to providing information on the cloud cover in oktas (i.e., the eighths of the sky obscured by clouds) to accompany the UVER data. The All-Sky Imager is a custom adaptation of a scientific CCD camera, using a digital color video camera mounted with a fish-eye lens (180 FOV) pointing to the zenith. Additionally, the camera is environmentally protected and a solar-shadow system is used to avoid direct incidence of the Sun beam on the lens.

The total ozone data used in this work have been provided by the ESA Global Ozone Monitoring Experiment (GOME) (Burrows et al., 1999) which recorded daily measurements from July 1995 to June 2011. Its current operational algorithm for the retrieval of total ozone data is the GOME Data Processor Version (GDP) Version 4.x (van Roozendael et al., 2006). The accuracy of the total ozone columns retrieved by this GOME retrieval algorithm is, in average, very high (within a few percent) (Balis et al., 2007; Antón et al., 2008; Loyola et al., 2011).

3. Results and discussion

The diurnal evolution of the experimental UVI data at Granada for two consecutive days in June 2009 (days 15 and 16) is shown in Fig. 1. Additionally, the evolution of the theoretical clear-sky UVI values for the day 16 has also been

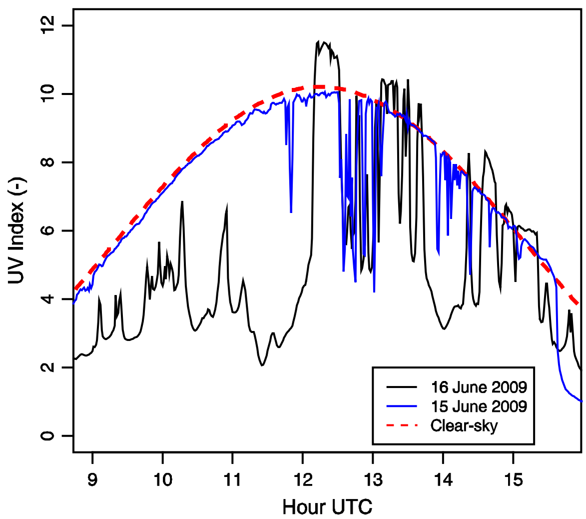

Fig. 1. Diurnal evolution of the experimental UVI data at Granada on 15 (blue) and 16 (black) June 2009. The dotted red curve represents the evolution of the modeled clear-sky UVI values for the day 16. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

added to the plot. These simulated data are derived from the following empirical expression (Madronich, 2007):

$$\mathrm{UVI} = a(\mu_0)^b \left(\frac{\mathrm{TOC}}{300}\right)^c \quad (1)$$

where μ_0 is the cosine of the solar zenith angle and TOC is the total ozone column which has been measured by the GOME instrument, providing a value of 305 Dobson Unit (DU) over Granada for the day 16. These modeled UVI data can be assumed valid for the day 15 since the TOC values present a small day-to-day variability in summer at the Iberian Peninsula (Antón et al., 2011b) due to that the dynamical variability in mid-latitude stratosphere is practically absent during this season. Thus, the TOC values recorded by GOME on 13 and 19 June were 307 and 309 DU, respectively, very close to the value measure on day 16. Antón et al. (2011c) calculated the coefficients (a, b and c) for Granada from a regression analysis using experimental UVI data measured under clear sky conditions. These authors validated this clear sky model using data recorded during a period not used for calculating fitting coefficients. The validation results reported an excellent agreement between experimental and simulated data with a mean absolute relative difference around 2.5%.

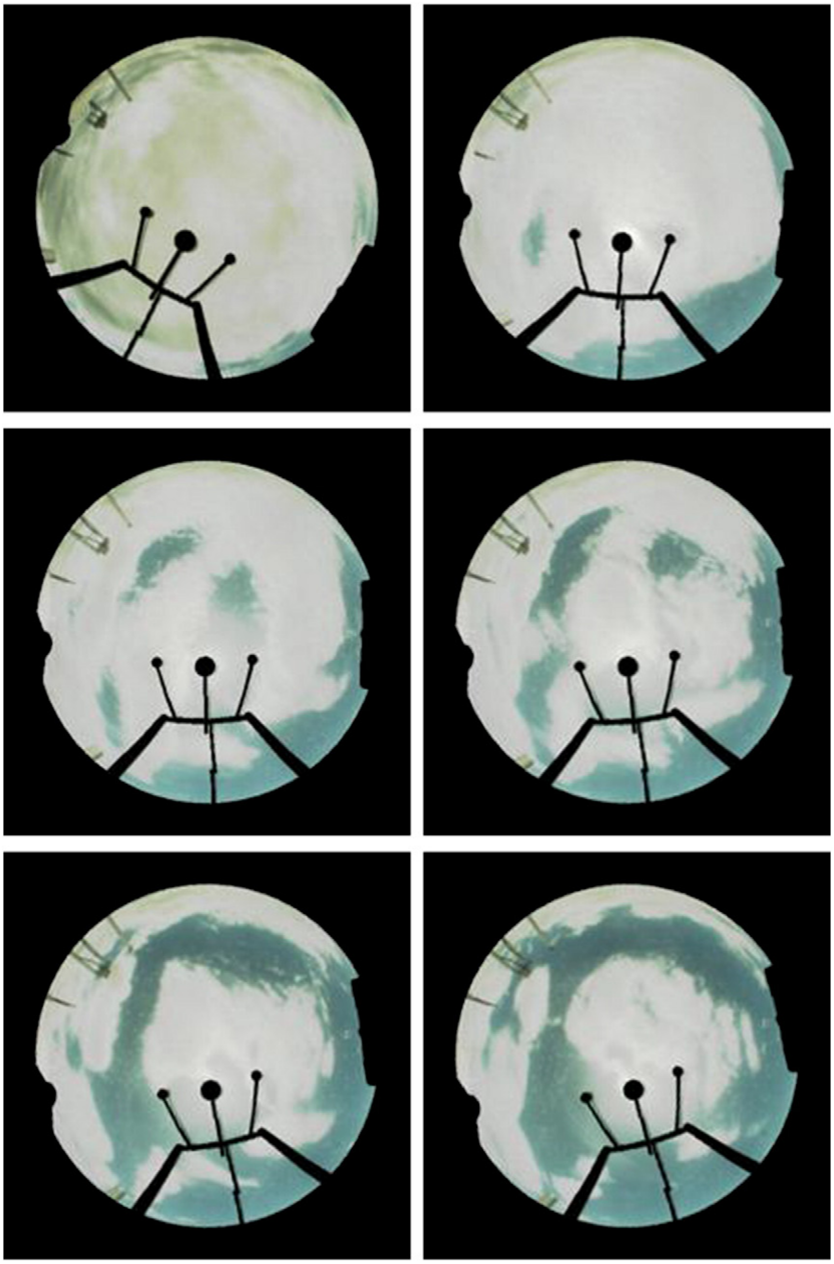

Fig. 2. Images taken with the All-Sky Imager on 3 February 2009 at 11.40 GMT (top left), 12:10 GMT (top right), 12:15 GMT (middle left), 12:20 GMT (middle right), 12:25 GMT (bottom left) and 12:30 GMT (bottom right).

It can be seen that the experimental UVI data recorded on 15 June show cloud-free conditions until midday. For this period, the evolution of the experimental and modeled clear sky UVI values presents a very similar behavior which points out the great reliability of the empirical model used in this work. The UVI exhibits a high value at solar noon (~10) which is mainly due to three factors: the proximity to the summer solstice, cloud-free conditions and, finally, the relatively small TOC value. Thus, the TOC for the day 16 (305 DU) corresponds with the percentile 15 of the GOME data recorded in June for the period 1995–2011. This high UVI at Granada is in agreement with maximum UVI data reported for other sites located at similar latitudes (Martínez-Lozano et al., 2002; Marín et al., 2005; Alados et al., 2007; Antón et al., 2009).

The UVI evolution on 16 June shows a strong variability due to changing cloud cover during this day. UVI ranges from low values for overcast conditions to values clearly higher than the corresponding clear-sky conditions (cloud enhancement events) which are observed after midday. We are focused on the longest and more intense of these episodes which occurred around midday. It can be seen the strong increase that the UVI suffers changing from 2.6 at 11:40 to 10.4 at 12:10 GMT. Thus, the UVI shows a relative increase of a factor 4 in the course of only 30 min. The UVI remains above 10 for about 20 min until 12:30, showing the maximum value ~11.5 during several minutes around 12:20. This period is classified as the extreme erythemal risk by the European Cost 713 Action "UV-B Forecasting" (Vanicek et al., 2000) which established a universal category with four UVI intervals: 0–3 (low erythemal risk), 4–6 (moderate), 7–9 (high) and >10 (extreme).

In order to quantify the impact of that enhancement event on the sunburn of human skin, we calculated the erythemal weighted exposure during the studied episode. The integration of the 1-min UVER values in the period of 20 min provided an UV erythemal dose of 350 J/m^2. The clinically observed minimal erythemal dose (MED) is defined as the minimal amount of energy required to produce a qualifying erythemal response (visible reddening 24 h after exposure) (Lucas et al., 2006). This parameter depends on the skin type, being equivalent to an efficient erythemal exposure of 250 and 350 J/m^2 for the skin phototype 2 (sometimes tans, usually burns) and 3 (usually tans, sometimes burns), respectively (Vanicek et al., 2000), which are the most common skin phototypes in Spain. Therefore, the UV erythemal dose obtained during the strong cloud enhancement event at Granada corresponds to 1.4 (skin type 2) and 1.0 (skin type 3) MED, highlighting the potential harmful impact over the skin of the short-term extreme episode analyzed in this work.

The Eq. (1) allows estimating the TOC value that would cause a UVI = 11.5 at solar noon under cloud-free conditions on 16 June at Granada. Thus, TOC should present a value of 265 DU in the study date to reach that extreme UVI value. This represents a decrease of around 40 DU (~13%) compared to the TOC value recorded on day 16, in itself already small. The analysis of TOC data over Granada by means of satellite GOME instrument shows that the minimum TOC value recorded in June for the period 1995–2011 was 286 DU which would produce a UVI ~ 10.7 under cloud-free conditions. Therefore, the extreme enhancement event analyzed in this work cause an UVI substantially higher than the largest index that could origin the natural TOC variations in June over the study site.

Fig. 2 (top, left) shows an image taken with the All-Sky Imager at 11:40 GMT which exhibits completely overcast conditions with a dark gray color of the cloud base suggesting an elevate cloud thickness. These conditions cause a persistent reduction in the UV solar radiation reaching the Earth's surface (UVI = 2.6). Additionally, Fig. 2 also shows five successive images between 12:10 and 12:30 (cloud enhancement period, UVI above 10) with partly cloudy conditions (5–7 oktas) in which the Sun was surrounded by white cumulus clouds. These conditions lead to little or no reduction in the direct component and, simultaneously, higher levels of the diffuse component at the surface compared to clear-sky atmosphere. Several authors (e.g., Mims and Frederick, 1994; Cede et al., 2002; Pfister et al., 2003; Crawford et al., 2003; Schade et al., 2007) have argued that this enhancement of the downward diffuse radiation may be associated with two different contributions: (1) multiple reflection of direct solar radiation in the lateral parts of clouds and, (2) increased forward scattering due to the photons scattered inside clouds and reflected again from cloud sides.

We would like to emphasize that a high protection against the UV radiation should be maintained even in days with large horizontal extension of clouds since those days can become more dangerous for human health than cloud-free days. In future work a whole statistical analysis of the UV enhancement episodes associated with broken cloud fields occurred in the period 2006–2011 will be performed at Granada.

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