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TELLUS

Application of an analytical formula for UV Index reconstructions for two locations in Southwestern Spain

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ABSTRACT

This paper focuses on the application of a simple analytical parameterization to the filling of the Ultraviolet Index (UVI) data gaps, and the reconstruction of past UVI values at Badajoz and Caceres (Southwestern Spain). The empirical model involves three independent variables: the solar zenith angle, the total ozone column and the clearness index. Regarding the first application, daily UVI was estimated for more than 30 days when UV measurements were not available in 2007. For these cases, the missing UVI data were replaced by estimated values, thus affecting the UVI annual mean and median. Regarding the second application, the reconstruction of past UVI time-series (1950–2000) is performed only for clear-sky cases (cloud and aerosol free conditions) using the COST 726 total ozone climatology. The linear UVI trends for two periods (1957–1978 and 1979–2000) are calculated for summer months using linear least squares fits. Both locations show statistically significant UVI trends for the most recent period 1979–2000, with values of +4.4 ± 1.6% per decade for Badajoz, and +4.9 ± 1.8% per decade for Caceres. This result is mainly driven by the ozone decline at northern mid-latitudes during this period. No significant trend is found for the other analysed period.

1. Introduction

Although ultraviolet (UV) radiation (100–400 nm) represents only 8% of the solar spectrum at the top of the atmosphere (Iqbal, 1983), it plays a major role in the chemical processes taking place in the atmosphere. In addition, the incident UV radiation at the Earth's surface has a strong biological influence on human beings, and on terrestrial and aquatic ecosystems (Diffey, 1991). It is well known that UV radiation can induce detrimental effects on human health (particularly on the skin, sight and immune system; World Health Organization (WHO), 1995; Lucas et al., 2006). Increases in the exposure of UV radiation combined with more outdoor activities have favoured a quick rise in those harmful effects. Therefore, the analysis of long-term UV measurements and trend detection at different locations becomes a high priority in scientific research [United Nations Environment Programme (UNEP), 2006].

The variable commonly used to inform the public about the potentially harmful effects of UV radiation is the UV Index (UVI; WMO, 1998). This informative variable is directly derived from the ultraviolet erythemal radiation (UVER) measured at surface which is quantified by weighting the solar UV radiation with the erythemal spectral response (McKinlay and Diffey, 1987).

Time-series of UVI measurements in Spain cover only the last 10 years (Antón et al., 2009a and references therein), which is unfortunately too short for reliable climatology and trend analysis (Weatherhead et al., 1998). Thus, reconstruction methods based on radiative transfer or empirical models are required to build longer time-series of this variable (e.g. Bodeker and McKenzie, 1996; Gantner et al., 2000; Kaurola et al., 2000; Fioletov et al., 2001; Eerme et al., 2002; Diaz et al., 2003; Engelsen et al., 2004; Trepte and Winkler, 2004; Lindfors et al., 2003, 2007; Lindfors and Vuilleumier, 2005; den Outer et al., 2005; 2010; Junk et al., 2007; Chuvaroba, 2008; Rieder et al., 2008). The utility of those models is not only focused on the reconstruction of past UV records, but also offer the possibility of filling gaps in databases (Mateos et al., 2010).

In this framework, the main objective of this paper is to reconstruct daily UVI time-series for two locations of Southwestern Spain using an empirical model given by Antón et al. (2011) which relates the UVI to three independent variables: total ozone column (TOC), clearness index (k_t) and solar zenith angle (SZA). In this work, this analytic method is applied for filling the data gaps in UVI databases and for the reconstruction of clear-sky UVI values

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during the period 1950–2000 using TOC values derived from the COST 726 total ozone climatology (Krzyścin, 2008). Although there are several works in the literature related to the estimation of UV radiation values in the Iberian Peninsula (e.g. Foyo-Moreno et al., 1999, 2007; Badosa et al., 2005; Antón et al., 2009a, 2009b; Mateos et al., 2010), to our knowledge no study on the reconstruction of past UV data in this region has been published to date.

The instrumentation and the data used in this paper are described in Section 2. Section 3 describes the analytical expression used in the reconstruction work. Section 4 presents and discusses the results obtained in this paper and, finally, Section 5 summarizes the main conclusions.

2. Data

UVER data were measured on a plane and horizontal surface in Badajoz (38.99°N, 7.01°W, 199 m a.s.l.), and Caceres (39.48°N, 6.34°W, 397 m a.s.l.) by UV-S-E-T broadband radiometers manufactured by Kipp & Zonen (Delft, The Netherlands). These two ground-based stations are characterized by a high frequency of cloud-free days during the year, particularly during the summer (Serrano et al., 2006). The output of the two broadband radiometers was sampled every 10 s and its 1-min average was recorded on a Campbell CR10X data acquisition system.

The spectral and angular characterization of these two instruments was performed during the first Spanish calibration campaign of ultraviolet broad-band radiometers at the 'El Arenosillo' INTA station in Huelva (Spain), from 20 August to 15 September 2007 (Vilaplana et al., 2009). This campaign also included the absolute calibration of the radiometers which was performed through the outdoor intercomparison with respect to a well-calibrated Brewer spectroradiometer. All this information is utilized for converting the raw signal of broadband UV radiometers into erythemal units (expressed in W m^{-2}) using the expression proposed by Webb et al. (2006). This new calibration method (two-step method) leads to a great improvement relative to the previous procedure (one-step method) which only consists in the direct comparison between the output signal of the broadband radiometers and the erythemally integrated spectral irradiance given by one reference Brewer spectrophotometer (Cancillo et al., 2005). Although the calibration factors obtained with the one-step method are only valid for the total ozone and SZAs recorded during the outdoor intercomparison, the calibration factors derived from the two-step method account for the total ozone and SZA dependence along the complete ozone and angle ranges (Bais et al., 1999). Therefore, the two-step method is recommended by several organizations responsible for calibration protocols, because of its higher accuracy (Bais et al., 1999; Webb et al., 2003).

It is well known that the spectral response of the broadband UV radiometers changes with time, mainly attributable to the aging effect of these instruments. For this reason, and to work with UVER data that are as accurate as possible, we have applied the calibration derived from the campaign described above to the values recorded around 2007 (period 2006–2008). The UV Index corresponding to each UVER value is calculated by multiplying these values by 40 (WMO, 1998).

The total ozone data used in this study correspond to the COST 726 ozone climatology (1950–2009; Krzyścin, 2008), which was developed within the scope of European Union's Action COST 726 project 'Long term changes and climatology of UV radiation over Europe'. This European ozone climatology is derived from a statistical model which was trained on satellite data over the period 1979–2004 (NIWA assimilated total column ozone data base) and over the period 2005–2009 (OMI total ozone data base). The total ozone values were calculated from the reconstruction backward in time using the regression constants derived from the result of the training with satellite data, and time-series of meteorological variables and atmospheric circulation indices. The COST 726 ozone data base consists of daily total values for a rectangular area with longitude from 25.625°W to 35.625°E and latitude from 30.5°N to 80.5°N. The spatial resolution is 1° in the latitudinal and 1.25° in the longitudinal direction. Detailed description of this COST 726 ozone climatology and its validation can be found in the work of Krzyścin (2008). The trend analysis of the total ozone values derived from this climatology can be found in the paper of Krzyścin and Borkowski (2008).

In this work, the atmospheric clearness is characterized by the transmissivity of solar total horizontal irradiance in the atmosphere. This variable, also named clearness index (k_t), is obtained as the ratio of the total solar irradiance on a horizontal surface to the extraterrestrial total irradiance on a horizontal surface. Total solar irradiance (310–2800 nm) is measured by a pyranometer Kipp & Zonen CM-6B collocated in each station. The clearness index is mainly associated with cloudiness, characterizing the absorption and scattering processes of total solar irradiance in the atmosphere. In addition, the attenuation processes related to the aerosols and the molecular constituents of the atmosphere show also significant effects on the clearness index, that is this index is smaller than 1 for a completely cloud-free sky.

3. Methodology

Antón et al. (2011) proposed the following general analytic formula for the estimation of UVI under all sky conditions:

$$\mathrm{UVI} = a\left(\frac{\mu_0}{0.96}\right)^b \left(\frac{\mathrm{TOC}}{315}\right)^c \left(\frac{k_t}{0.91}\right)^d, \qquad (1)$$

where μ_0 is the cosine of the SZA, TOC is the total ozone column in Dobson Units (DU) and k_t is the clearness index. The coefficient a represents the UVI value for the following specific conditions in Southwestern Spain: the smallest SZA (summer solstice; $\mu_0 = 0.96$), TOC equal to 315 DU (annual mean value) and k_t equal to 0.91 (99‰ of all k_t data). The coefficients b, c and d show the sensitivity of UVI to changes in the three independent variables: SZA, TOC and k_t, respectively. The coefficients of the empirical model (eq. 1) were derived by Antón et al. (2011) from a multiple regression analysis using the least squares approach. Daily data were selected for the period between January 2006 and December 2007. The UVI and k_t data correspond to values recorded at solar noon (maximum daily μ_0). In addition, TOC corresponds to the daily value provided by the COST 726 ozone climatology. Values of a, b, c and d were found to be respectively 9.63 ± 0.07, 2.24 ± 0.02, 1.14 ± 0.04 and 0.75 ± 0.01 for Badajoz; and 9.85 ± 0.06, 2.35 ± 0.01, -1.30 ± 0.03 and 0.76 ± 0.01 for Caceres and these values are again used here with expression 1 to fill gaps in UVI databases and the reconstruction of past UVI records.

4. Results and discussion

4.1. Application to fill data gaps

The broadband UV radiometers belonging to the Extremadura UV radiometric network suffer from some periods without UVER measurements mainly due to the maintenance of these instruments and their participation in calibration campaigns. Thus, for example, both UV radiometers were sent to the manufacturer in the Netherlands during the period March to May 2004 to measure their spectral response. In addition, the instruments have been moved to the 'El Arenosillo' ESAT/INTA station every two years for outdoor intercomparison with respect to a well-calibrated Brewer spectroradiometer #150 (Cancillo et al., 2005; Vilaplana et al., 2009). The mentioned calibration field campaigns lasted for about 1 month.

The empirical models can be used for filling existing gaps in the database whenever the information about the independent variables is available during these periods. This is the case for pyranometers for measuring the total solar irradiance, which continued recording data in Badajoz and Caceres during the absence of the UV radiometers in these locations. Thus, the clearness index is available for those periods without UVI data, allowing estimations of UVI by means of the proposed empirical model (eq. 1).

Figure 1 shows two plots with the measured and estimated UVI time evolution in Badajoz and Caceres during the year 2007. Two vertical dashed lines mark the limits of the period without experimental data due to the participation of the UV broad-band instruments in the calibration campaign at El Arenosillo Station from 20 August to 15 September 2007. The mean absolute value of the relative differences between modelled and measured UVI data ($UVI^{mod} - UVI^{mea}/UVI^{mea}$) for the year 2007 is 5.8% and 4.6% for Badajoz and Caceres, respectively. This excellent agreement when UVI observations are available supports the reliability of the reconstructed time-series.

The original 319 daily UVI measurements during 2007 in Badajoz have increased up to 352 values using the empirical model (the reconstructed data represents 9.4% of all). In Caceres, for the year 2007, the time-series increased from 310 to 352 values when UVI was reconstructed by the model (the reconstructed data represents 11.9% of all). These notable differences in the number of data between both time-series affect the annual statistical parameters of the UVI at the two locations. For example, for Badajoz, the mean (median) annual value changes from 4.40 (4.17) for the measured dataset to 4.52 (3.80) for the reconstructed data set.

4.2. Application to reconstruct past data for cloud-free days

The empirical model proposed in this paper (eq. 1) allows us to estimate UVI values for all sky conditions. However, because the clearness index is only available for our locations after 2000, the reconstruction of the past UVI data must be performed for clearness cases (cloud-free and constant low-load aerosol conditions). Thus, a constant clearness index equal to 0.91 was considered in the empirical models for Badajoz and Caceres. This value was obtained as the 99‰ of all daily clearness indexes during the period of available measurements (2001–2008) at each location.

The temporal evolution of the reconstructed UVI data for the whole period 1950–2000 is shown in Fig. 2 for Badajoz and Caceres separately. Each point in the plot represents the annual summer mean value of the reconstructed UVI data calculated as the average of the four months around the summer solstice (May to August). These months were selected as the period of the year when the highest UVI values are recorded (Antón et al., 2009a). In addition, the prevailing cloud-free situation in Southwestern Spain during these months (Serrano et al., 2006) allows the clear-sky reconstructed UVI values to be considered very close to the real past UVI values. From the two plots of Fig. 2, similar reconstructed UVI values can be seen for the two ground-based stations during the whole period. Thus, the relative difference between the reconstructed values ($UVI^{Caceres} - UVI^{Badajoz}/UVI^{Badajoz}$) for the period 1950–2000 is only about 4%.

This reconstructed UVI values are derived assuming a constant clearness index (99‰ of daily clearness index values between 2001 and 2008) as explained earlier. The variability of this index is mainly related to cloudiness and atmospheric aerosols. In this sense, significant declines in both aerosol optical depth (e.g. Cheymol and De Baker, 2003; Kazadzis et al., 2007; Ruckstuhl et al., 2008) and cloudiness (e.g. Lindfors and Vuilleumier, 2005; Rieder et al., 2008; den Outer et al., 2010) have been reported since early 1990s in Europe. In addition, it is well known that the maximum atmospheric turbidity was reached in Europe during the period 1970–1990 (e.g. Tegen et al., 2000). Thus, the 99‰ of daily clearness index values obtained in Southwestern Spain between 2001 and 2008 may be higher than the

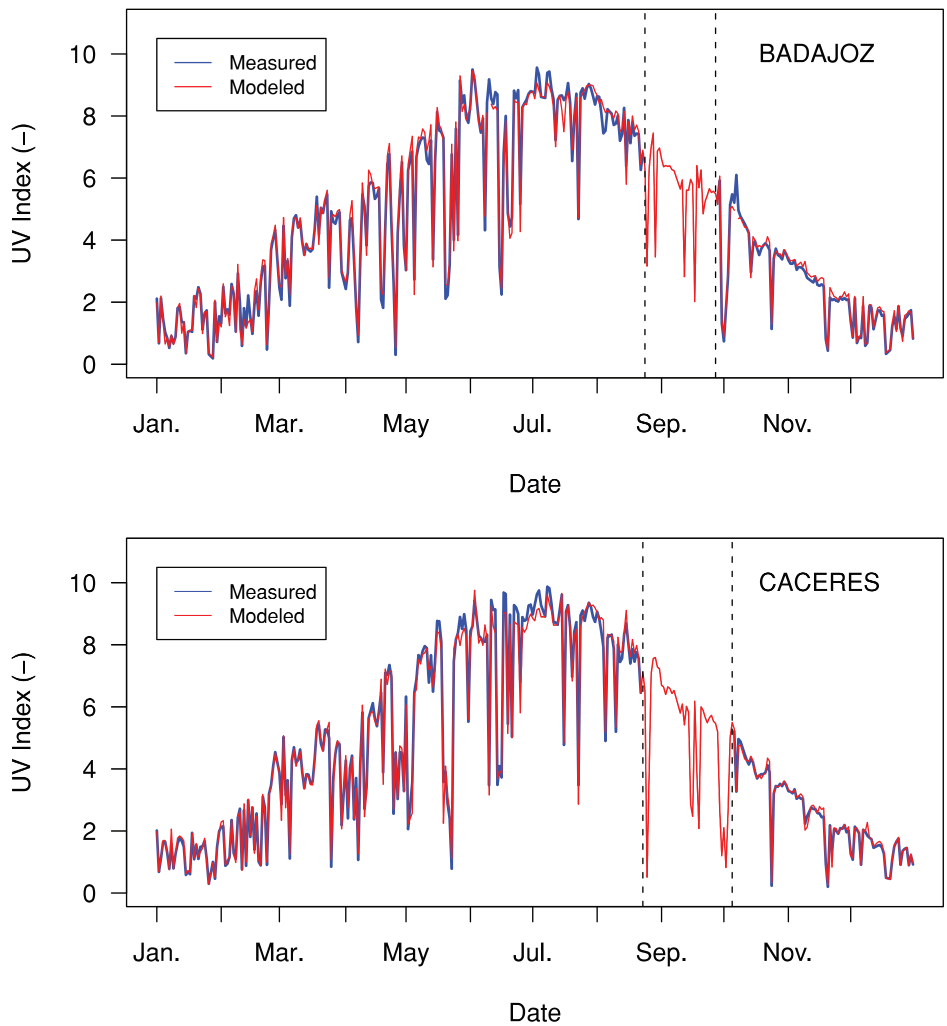

Fig. 1. Evolution of the measured and estimated daily UVI data at Badajoz (top) and Caceres (bottom) for the year 2007. The time between the vertical dashed lines represents the period without experimental UVI data.

same percentile for the 1990s and previous decades. This fact could likely result in slightly overestimated reconstructed UVI values between the 1970s and 1990s.

The linear long-term trends were obtained as least squares fits of the annual summer mean values (calculated as detailed above). Figure 2 shows a high interannual variability of summer UVI values, which makes the trend analysis notably sensitive to the length of the data set (Weatherhead et al., 1998). In this sense, we work with two subperiods of 22 years: from 1957 to 1978, and from 1979 to 2000. The linear trends were calculated for each interval at the two locations. The trends for the second period 1979–2000 have been added to the figure. It can be seen that the summer trends for the period 1979–2000 are clearly positive in the two locations, suggesting a possible connection to the ozone decline at middle-latitudes which started about the late 1970s and stopped about middle 1990s (Krzyścin, 2006; Harris et al., 2008).

Table 1 shows the results of the summer trend analyses, together with their standard errors, expressed in UVI units and in percentage with respect to the average UVI value for the months May to August during each period. The trends for the period 1979–2000 are $+4.4 \pm 1.6\%$ per decade for Badajoz, and $+4.9 \pm 1.8\%$ per decade for Caceres, being both statistically significant at the 95% confidence level. It should be emphasized that these results together with the prevailing cloud-free conditions during summer in Southwestern Spain suggest that the increase in UVI in this region has been real between 1979 and 2000 during summer. The empirical model used in this work for the reconstruction of past clear-sky UVI data involves two inputs: the solar zenith angle and the total ozone column. Thus, the significant positive UVI trends obtained for the period 1979–2000 at Badajoz and Caceres are related to the decline of the total ozone data for the same period (about -3.6% per decade in the two locations).

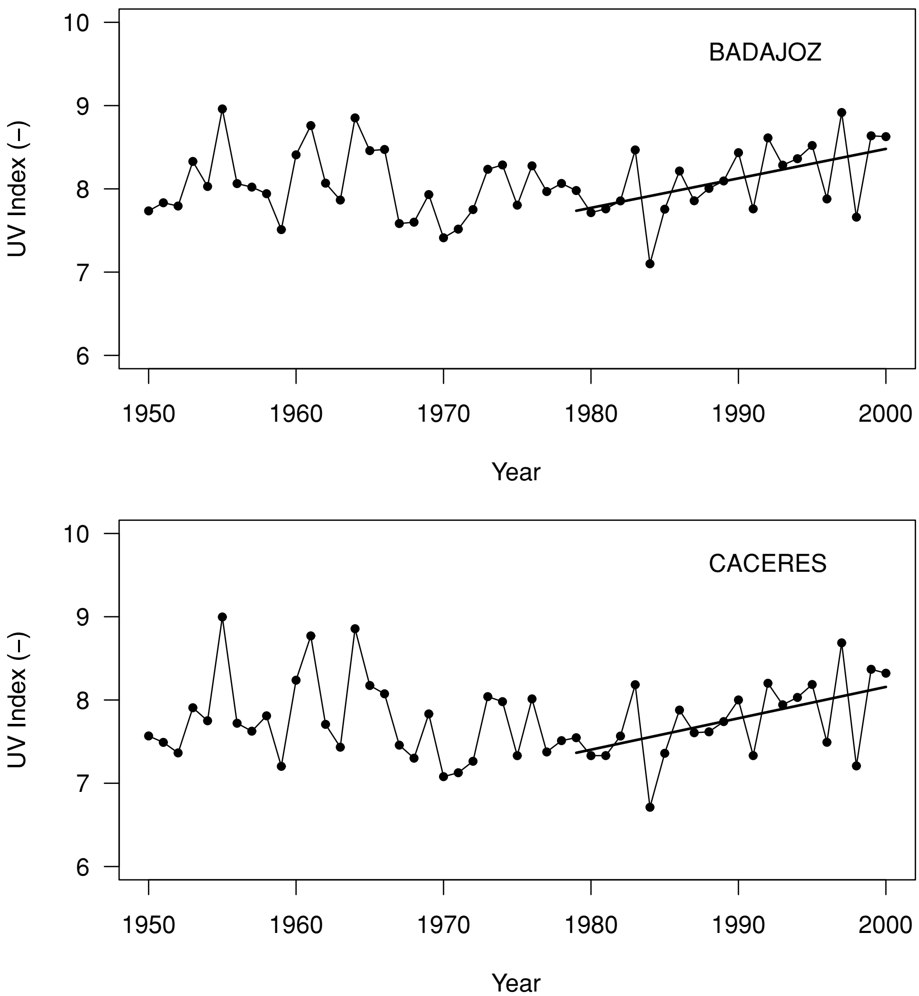

Fig. 2. Evolution of the annual mean value (May to August) of the reconstructed clear-sky UVI data at Badajoz (top) and Caceres (bottom) for the period 1950–2000. Linear trend over the period 1979–2000 is also shown.

The results of the UVI trend analysis for Badajoz and Caceres are in broad agreement with the results found in the literature. Among of them, Fioletov et al. (2001) calculated linear trends in reconstructed cloud-free UVER for three locations in Canada, showing values between +3.3% and +5.4% per decade for summer (May to August) during 1979–1997. The work of den Outer et al. (2005) showed that the annual UVER dose received at Bilthoven (the Netherlands) for cloud-free conditions was 3.1 ± 0.8% per decade over the period 1979–2003. Kaurola et al. (2000) found a statistically significant increasing trend of 5.4 percent per decade in the yearly reconstructed UV doses at Jokioinen (Finland) for the period 1979–1997. Lindfors et al. (2007) analysed the past clear-sky UVER values at four stations in northern Europe, finding slight positive annual trends over the period 1983–2005. Krzyścin et al. (2010) found positive UVER trends (5.5 ± 1.0% per decade) at Belsk (Poland) for the period of 1976–2008 in the seasonal mean for the warm subperiod of the year (April–October). Chubarova (2008) performed a long-term analysis (1968–2006) of reconstructed UVER data at Moscow (Russia), reporting linear statistically significant positive trends (∼6% per decade) since 1980. UV reconstruction data were analysed by den Outer et al. (2010) for eight sites in Europe, showing linear trends from +0.3 ± 0.1% to +0.6 ± 0.2% per year

Table 1. Linear trends (±standard error) in UVI units per decade for summer (May to August) over two periods (1957–1978 and 1979–2000) in Badajoz and Caceres

	1957–1978	1979–2000
Badajoz	−0.09 ± 0.13	+ 0.33 ± 0.12
	(−1.1 ± 1.7)	(+ 4.4 ± 1.6)
Caceres	−0.21 ± 0.16	+ 0.38 ± 0.14
	(−2.7 ± 2.1)	(+ 4.9 ± 1.8)

Note: Results in percent per decade are shown in parentheses.

for the period 1980–2006. Our results also agree with the works of Gantner et al. (2000) and Trepte and Winkler (2004), which analysed the UV levels at Hohenpeissenberg (Germany), showing statistically significant increasing trends in clear-sky noontime UVER values for the months between March and September over the periods 1968–1997 and 1968–2001, respectively.

Finally, Table 1 also shows that the linear trends for the period 1957–1978 were slightly negative. Nevertheless, these trends were not statistically significant at the 95% confidence level. This result shows the high impact that the applied time range has on the trends and their uncertainties.

5. Conclusions

The application of a simple analytic model to the reconstruction of UVI data has allowed filling short gaps in UVI measurement series for two locations in Southwestern Spain under all sky conditions. Thus, the UVI has been estimated for more than 30 days with missing data during 2007. In addition, the reconstruction of past UVI time-series values (1950–2000) has been performed using the model for clear-sky conditions. Statistically significant UVI trends were found for Badajoz (+4.4% per decade) and Caceres (+4.9% per decade) for summer months during the period 1979–2000. These results suggest that the UVI values in summer increased during this period in Southwestern Spain. No significant trends were found for the period 1957–1978.

We would like to point out that experimental measurements of UV data using reliable instruments are necessary. Nevertheless, the reconstruction methods are of great importance, because they allow extension of the UV information to periods when direct measurements are not available.

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