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An empirical model to predict the UV-index based on solar zenith angles and total ozone

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The clear sky UV-index is expressed as a function of two predictable quantities: the solar zenith angle and total ozone. This function is derived by fitting the measurements of total ozone and the UV-index obtained from two instruments, one in the mid-latitudes and one in the tropics. The shape of the function was chosen so that it represents the essentials of the underlying physics. This new function gives good results for all solar zenith angles between 0° and 90° and a wide range of total ozone values.

1. Introduction

This paper focuses on the computation of the UV-index (UVI) (WMO 1995) for operational forecasts. The UVI is a measure for the amount of ultraviolet sunlight relevant for erythema (sunburn) (McKinley & Diffey 1987). The motivation for forecasting UVI is presented elsewhere (de Backer et al. 2001) and needs not to be repeated here. In designing an operational forecast scheme for UVI, we are faced with two questions: how to predict the relevant atmospheric parameters (e.g. the distribution of ozone and aerosol), and how to calculate the UVI given these parameters. The first is addressed in another paper (Eskes et al. 2002); in this paper we will concentrate on the second question. Two methods have been used to calculate UVI. One method is to solve the radiation transfer equation for a number of wavelengths in the ultraviolet (UV) band and then to compute the UVI from the resulting UV spectrum at the ground (Long et al. 1996; Lemus-Deschamps et al. 1999). This can be done with high confidence (van Weele et al. 2001), but it requires extensive computations, and many assumptions about atmospheric parameters that are not well known, or difficult to predict (see section 2). The other method is to use a regression equation, which has been obtained by fitting observed UVIs to a limited set of atmospheric parameters. This method, pioneered by Environment Canada (Burrows et al. 1994), is computationally efficient, easy to use and has been adopted by others (Austin et al. 1994). The equation of Burrows et al. (1994), however, is limited to a specific range of Solar Zenith Angle (SZA) values that are relevant for noontime in the Canadian summer, and does not reproduce the measurements taken at the tropical station at Paramaribo.

In this paper we derive a revised regression equation, valid for $0° < \mathrm{SZA} < 90°$ and a wide range of ozone values. We expect that this equation can be applied globally, except possibly in high mountains.

In section 2 we discuss the atmospheric parameters relevant for a UVI forecast. In section 3 the data used are presented, together with the stations at De Bilt (Netherlands) and Paramaribo (Suriname). In section 4 we introduce the functions we have fitted, and obtain the results of the fitting. Finally, in section 5 we show examples of measured and computed UVI for both stations.

2. Relevant parameters

Computation of the ultraviolet spectrum at the Earth's surface (and hence the UVI) typically requires knowledge of a number of astronomical and meteorological parameters. Most of these parameters will introduce some degree of uncertainty in a UVI forecast. Typical problems are high temporal or spatial variability and lack of measurements and forecasting skill. Rough estimates of the resulting uncertainties in the UVI are described below and summarised in Table 1.

Clouds. An unbroken cloud layer typically reduces the UVI by 50 to 60% and even more during precipitation. A broken cloud layer can increase or decrease the UVI. At some locations cloud properties can be predicted with some success (see e.g. Long et al. 1996; Burrows 1997). At many places the spatial and temporal variability of the clouds is so high that forecasters prefer to issue 'clear sky' and 'overcast' UVI forecasts instead, thus eliminating this source of error.

Albedo. The ultraviolet albedo is quite low for most surfaces, and so the influence of the albedo on the UVI is minimal. Only a snow cover can have a high UV albedo, with values up to 0.8 (Feister & Grewe 1995). A UVB increase of 28% over a snow cover under clear sky conditions has been reported by McKenzie et al. (1998). Even higher values are possible in partially cloudy

Table 1. *Relevant parameters for computing UVI and a rough estimate of the introduced uncertainty in a practical forecast.*

Parameter	Uncertainty in UVI
Cloud amount and properties	>50%
Albedo (snow)	28%
Ozone profile	8%
Aerosol properties ($\tau = 0.42 \pm 0.26$)	5%
Altitude (1 km)	5%
Total ozone (3%)	4%
Geographical latitude (1°)	3%
Distance from Sun to Earth	3%
Stratospheric temperature (10°)	2%
Sulphur dioxide (1 DU)	1%

conditions, with large solar zenith angles (McKenzie et al. 1998).

Ozone profile. The distribution of ozone through the atmosphere has a remarkably strong influence on UVI. Model simulations show that the calculated UVI values increase by 8% when a mid-latitude ozone profile is replaced by a tropical profile, while keeping the total amount of ozone constant (van Weele et al. 2000). An enhanced ozone content in the boundary layer ('smog') will result in lower UVI values. A model study shows a decrease of about 3%.

Aerosol properties. At De Bilt the aerosol optical depth at 368 nm is regularly measured. The average optical depth is 0.346 ± 0.210, with a typical Angstrom parameter of 1.4. Ignoring the variations in aerosol by assuming typical values for the aerosol optical depth introduces an error of about 5% in the UVI.

Altitude. In the absence of snow, UVI will increase some 5% per kilometre altitude for high plateaus due to a decrease in Raleigh scattering. In mountainous regions with a detailed orography, or with an altitude-dependent snow cover, a much stronger altitude dependence of the UVI has been observed (Gröbner et al. 2000). The stations at De Bilt and Paramaribo are both located so close to sea level that this effect plays no significant role.

Total ozone. In mid-latitudes the total ozone distribution shows a substantial day-to-day variability. Both observations (Wauben & Kuik 1998) and state-of-the-art ozone forecasts (Eskes et al. 2002) introduce an uncertainty of 3% in the column-integrated amount of ozone. This leads to an error of 4% in UVI.

Spatial variability. A UVI forecast will be represented either by a single number being relevant for the whole country or region, or as isolines of constant UVI on a map. These presentations will cause an error in the UVI. Here we will estimate this error conservatively as 1° in latitude, which translates to an error in UVI of 3% because of the different SZA. The variation of the ozone field can introduce a similar error.

Sun–Earth distance. The distance between the Earth and the Sun is not constant. The solar irradiance deviates by ±3% around its mean value, with a maximum in January. This effect can be corrected easily.

Temperature. The ozone absorption coefficients are slightly temperature dependent. However, the stratospheric temperature can vary significantly, especially in the vicinity of the polar vortex. Ignoring this effect could give an error in the UVI forecast of 2%.

Trace gasses. Like ozone, sulphur dioxide (SO_2) absorbs ultraviolet sunlight. At both stations the amount of SO_2 is smaller than 1 Dobson Unit ($= 2.69 \times 10^{20}$ molecules/m^2) most of the time. Its effect on UVI is quite small, less than 1%. On the other hand, as the lifetime of tropospheric SO_2 is quite short, it is possible that substantially higher amounts can occur in some areas. The effects of other minor trace gases are of comparable magnitude.

In this paper we will not consider the effects of clouds on UVI; in other words, we will look only at clear sky UVI. Furthermore, we will only take total ozone, SZA and the distance between Sun and Earth explicitly into account. As we will use observed data only in this paper, 'typical' values for the other parameters will be implied in the resulting parameterisation. This will result in a maximum error of the order of 10% in the absence of a snow cover.

3. Data

In this work we use the data from two MKIII Brewer Spectrophotometers. The Brewer Spectrophotometer is a double monochromator for UV wavelengths. The instruments are located at De Bilt (high mid-latitude) and Paramaribo (tropics).

3.1. De Bilt station

The first Brewer (serial number 100) is located at De Bilt in the Netherlands, 52.10°N, 5.13°E, and is operated by the Royal Netherlands Meteorological Institute (KNMI). The instrument is located on the top of a building, some 15 metres above the ground, which is 2 metres above sea level. The site is surrounded by a mixture of grass fields, forests, urban areas and arable fields. There are no hills or mountains visible from this site. Despite its northerly location, snow cover is present only 19 days per year on average. The air quality is highly variable: the dominating westerly winds usually result in quite clear air, but when the wind is southerly, easterly or very weak, the air can be quite urban (dirty). The Brewer measures total ozone and ultraviolet light intermittently from sunrise till sunset. The cloud characteristics (as observed by a human observer) are recorded each hour, which may be correlated with Brewer data. Deep blue skies are very rare at this site. Even when 'cloud free' conditions are reported, a thin cirrus layer is almost always present. Routine measurements with Brewer no. 100 began on 1 January 1994. This instrument compared favourably with other spectrometers in an international inter-comparison campaign (Bais et al. 2001).

3.2. Paramaribo station

Brewer no.159 is located at Paramaribo, Suriname, 5.81°N, 55.21°W, and is operated by the Suriname Meteorological Service (MDS). The instrument is located on the top of a building, some 10 metres above the ground, which is 25 metres above sea level. The site is in a suburban environment, dominated by small trees and shrubs. There are no hills or mountains visible from this site. Most of the time the air is very clean, although some pollution from distant forest fires can occur. Twice per year the inter-tropical convergence zone migrates over the site: from December to July the air is from the Northern Hemisphere, and from August to November it is from the Southern Hemisphere. Clear skies are quite usual early in the morning, but later in the day clouds usually develop. The Brewer measures total ozone and ultraviolet light intermittently as long as the SZA is smaller than 60°. Routine measurements with Brewer no.159 began on 15 March 1999.

3.3. Brewer ozone measurements

The Brewers are used to measure the column-integrated amount of ozone in the atmosphere. In this study only so-called 'direct sun' measurements are used. In this mode, direct sunlight is measured quasi-simultaneously at six wavelengths, four of which (310.1, 313.5, 316.8, 320.1 nm) are used in the ozone retrieval algorithm (Kerr et al. 1985). The accuracy of the measurements is in the order of 2% (Wauben & Kuik 1998). Both Brewer instruments are compared with a travelling standard bi-annually, and show no significant offset or drift. In this study, we have used daily average ozone values.

3.4. UVI measurements

The UVI is calculated using the spectral UV measurements by the Brewer spectrophotometers. The UV-index is a dimensionless quantity defined as:

$$\mathrm{UVI} = \frac{1}{25\,\mathrm{mW/m^2}} \int S_\lambda E_\lambda \, d\lambda \qquad (1)$$

Here S_λ is the solar irradiance at the surface (mW/m^2/nm), and E_λ is the erythemal action spectrum, defined as follows: (McKinley & Diffey 1987)

$$\begin{aligned}
E_\lambda &= 1 && \text{for} \quad \lambda \le 298\,\mathrm{nm} \\
E_\lambda &= 10^{0.094(298-\lambda/\mathrm{nm})} && \text{for} \quad 298\,\mathrm{nm} < \lambda \le 328\,\mathrm{nm} \\
E_\lambda &= 10^{0.015(139-\lambda/\mathrm{nm})} && \text{for} \quad 328\,\mathrm{nm} < \lambda \le 400\,\mathrm{nm} \\
E_\lambda &= 0 && \text{for} \quad 400\,\mathrm{nm} < \lambda
\end{aligned} \qquad (2)$$

In this mode, the light scattered through a horizontal diffuser is sent through the spectrometers. The UV spectrum is scanned, one wavelength at a time, from 286.5 to 363.0 nm, in steps of 0.5 nm.

The lack of measurements of wavelengths below 286.5 nm does not pose a problem because this radiation is absorbed by oxygen and ozone, and does not penetrate to the surface. However, the lack of measurements between 363 and 400 nm does require attention. If this region of the spectrum was simply ignored an underestimate of UVI of the order of 7% can be expected. Here we have chosen to correct for this effect by changing the tail end of the action spectrum. The modified action spectrum E'_λ has been given the increased value of 1.11×10^{-3} between 336 nm and 363 nm, and set to zero above 363 nm. Calculations with a radiative transfer model show that this correction reduces the error in UVI to insignificant values. This correction method avoids putting undue emphasis on one single wavelength and so introducing noise in the UVI. Equation (1) is replaced by:

$$\mathrm{UVI} = \frac{1}{25\,\mathrm{mW/m^2}} \sum_{286.5}^{363} S_\lambda E'_\lambda \Delta\lambda \qquad (3)$$

The calibration of the Brewer UV scans is done on an irregular basis with NIST traceable standard lamps. Neither instrument shows a change in sensitivity of more than 3% per year, which is well below the estimated accuracy of 10% for this kind of calibration (Bais et al. 2001).

4. Method

In this section we will fit the UVI values to the total ozone measurements and SZAs. In order to keep the fitting as easy as possible, and to keep the underlying physics clear, we will first consider in an atmosphere without any ozone (section 4.1). The effects of ozone will be considered in section 4.2.

4.1. UVA

In this section we will consider an atmosphere without ozone. In this case the UVI will depend mainly on SZA and the distance from the Sun to the Earth. As a proxy for UVI in this case we will introduce 'UVA': the observed Brewer spectrum multiplied by a weighting function, which is nonzero in the spectral region where ozone does not absorb significantly. (A parabolic weighting function was used, peaking at 350 nm and nonzero between 340 and 360 nm.)

Now, if diffuse sky light would give an unimportant contribution to the measured UVA, the following relation would be a reasonable approximation:

$$\mathrm{UVA} = \left(\frac{D_0}{D}\right)^2 * S_0 * \mu_0 * \exp\left(-\frac{\tau_a}{\mu_0}\right) \qquad (4)$$

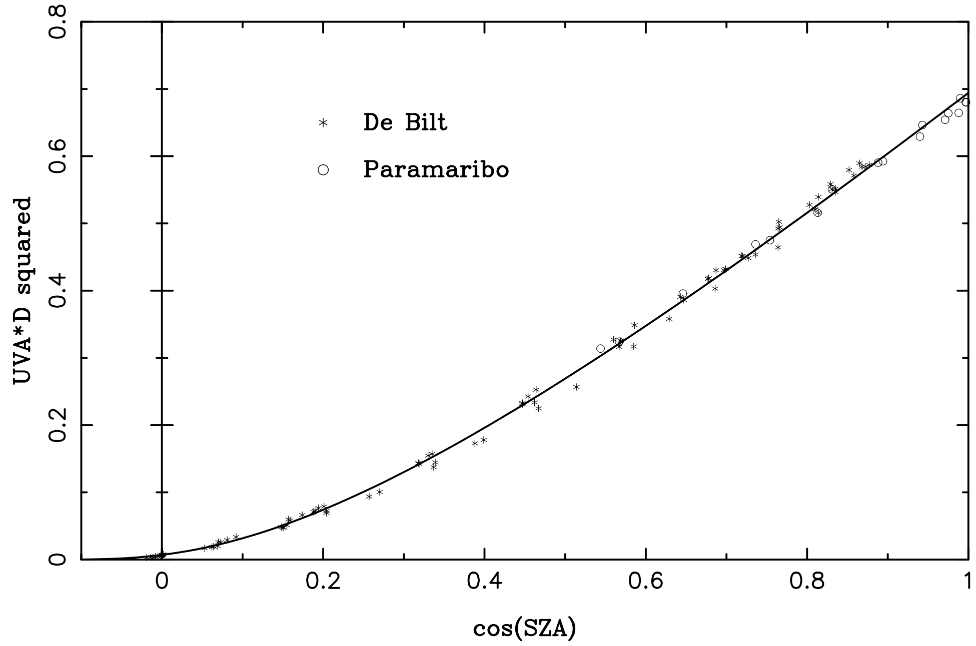

Figure 1. *UVA × D^2 as a function of cos(SZA). The symbols show the measurements, the curve shows the fit.*

Here D is the distance between the Sun and the Earth, D_0 is the average distance, $\mu_0 = \cos(SZA)$, S_0 is the extra-terrestrial value for UVA at $D = D_0$, and τ_a is the atmospheric extinction (molecular scattering and aerosol extinction) for SZA = 0.

The measurements are shown as symbols in Figure 1. This figure shows that for cos(SZA) = 0, UVA is still well above zero. Here scattered light obviously plays a role. In order to account for this we have added a small offset 'ε' to μ:

$$\mu_x = \mu_0 * (1 - \varepsilon) + \varepsilon \quad (5)$$

Equation (4) now becomes:

$$\mathrm{UVA} = \left(\frac{D_0}{D}\right)^2 * S * \mu_x * \exp\left(-\frac{\tau}{\mu_x}\right) \quad (6)$$

Data selection for fitting was rather strict. We only allowed data from completely cloud-free days. For De Bilt, the four brightest days of spring/ summer 2000 were chosen (10 April, 14 May, 8 June, 17 June). For Paramaribo, only one completely cloud-free day could be identified (17 September 1999). The rather limited amount of data is not a problem, as UVA does not depend on ozone, and the full range of SZA values is present in the data.

Equation (6) contains three free parameters, which were determined using a nonlinear fitting technique (MRQMIN; Press et al. 1986). The fitted values are:

$$S = 1.24\,\mathrm{Wm^{-2}\,nm^{-1}}$$

$$\varepsilon = 0.17$$

$$\tau = 0.58$$

The fit is shown as the curve in Figure 1. The root mean square error of this fit is in the order of 0.009 $\mathrm{Wm^{-2}\,nm^{-1}}$

4.2. UVI

The second step is to express the UVI as a function of UVA, μ_0, and total ozone (TO). As a first-order guess we assume that the extinction will depend mainly on the amount of ozone along the straight line from the Sun to the station (in first approximation TO/μ_0). So we will use the following predictor:

$$X = 1000 * \frac{\mu_0}{\mathrm{TO}} \quad (7)$$

In this case a large dataset is necessary because a substantial range in both TO and SZA values is required. For this case we collected all clear-sky UVI values from the Brewer at De Bilt for the period April–September 2000, 510 measurements in total. We also used all UVI measurements for Paramaribo in 1999, excluding the data for which UVA deviated from the fit discussed in section 4.1 for more than 10%, leaving 476 measurements.

The symbols in Figure 2 show the values of $\frac{\mathrm{UVI}}{\mathrm{UVA}}$ as function of X. A simple power law relation is emerging, although a weak dependency on TO still remains. We have fitted the following function:

$$\frac{\mathrm{UVI}}{\mathrm{UVA}} = F * X^G + \frac{H}{\mathrm{TO}} + J \quad (8)$$

Here the parameter J is included to allow for a nonzero UVI when X goes to zero, and H represents the small explicit ozone dependence. Again we used the

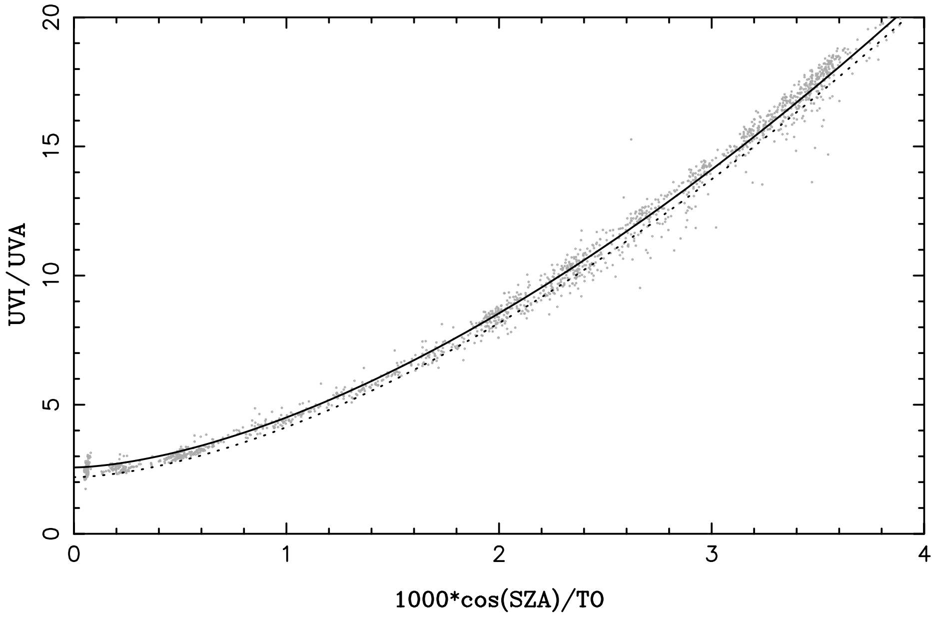

Figure 2. *UVI as function of UVA, SZA and TO. The full line shows the fit for 280 Dobson Units, the dotted line shows the fit for 450 Dobson Units. The symbols show all the data on which this fit is based.*

MRQMIN algorithm (Press et al. 1986). The results are:

$$F = 2.0$$

$$G = 1.62$$

$$H = 280.0$$

$$J = 1.4$$

In Figure 2, the fit for TO = 280 Dobson Units is shown as the solid curve, the dotted curve shows the fit for TO = 450 Dobson Units. The root mean square error of this fit is 0.20. (Instead of the power-law we also tried an exponential fit, but this gave a slightly worse result: 0.21).

5. Results

In this section we will give two examples of how the UVI calculations as described in section 4 compare with the measurements. In both cases we will use data that has not been used in the previous section.

The first case presents the UVI measurements at De Bilt on 11 May 2001. In the early morning there were some cirrus clouds, which cleared at 08h UT, but returned at

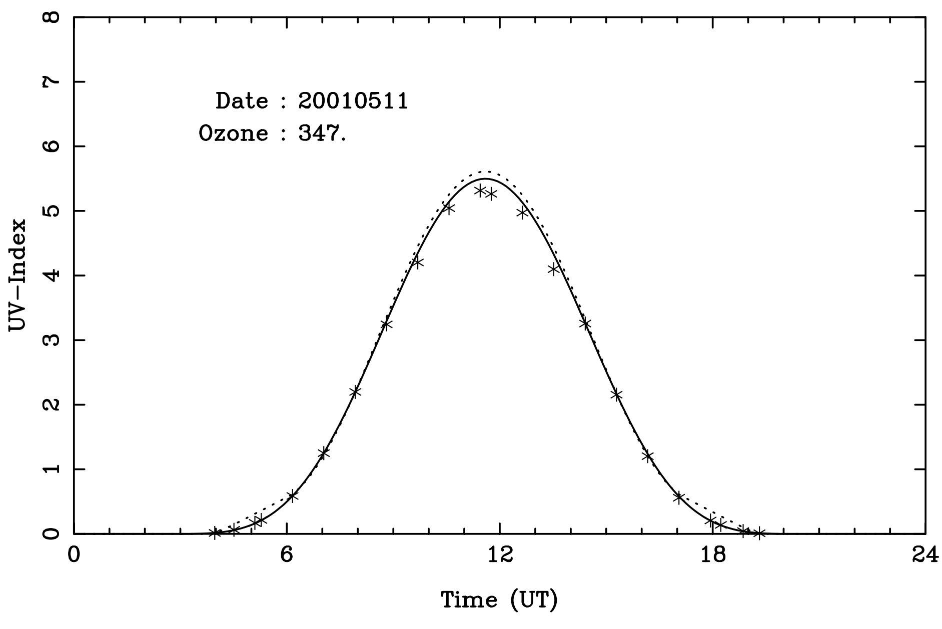

Figure 3. *UVI measurements at the mid-latitude station (De Bilt) on 11 May 2001. The solid line shows the clear sky UV-index parameterisation as derived in this paper. The dotted line shows the parameterisation of Burrows et al. (1994). Notice the differences for SZA greater than 70° (before 06h UT and after 17h UT).*

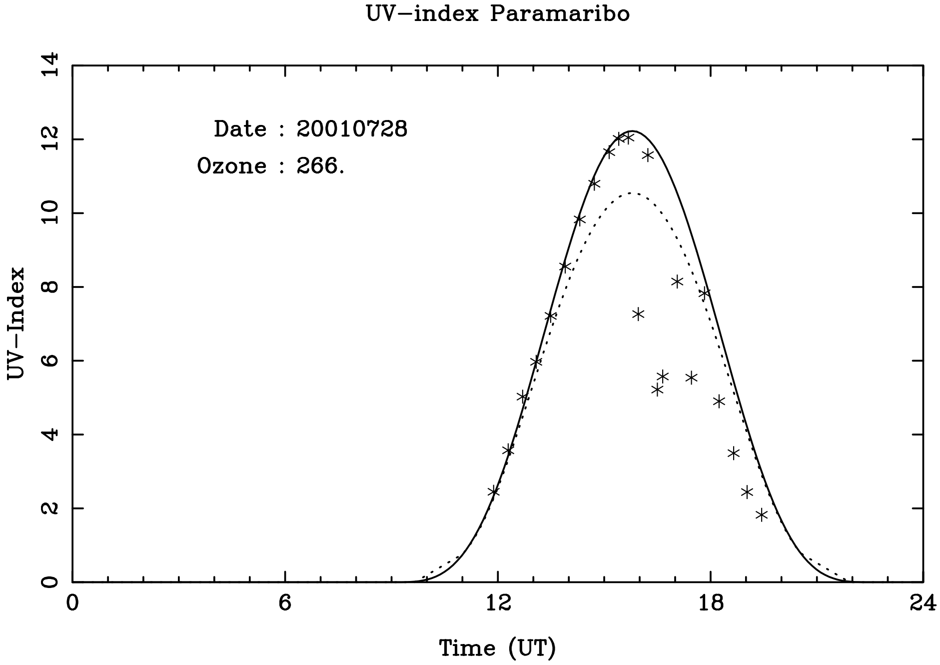

Figure 4. *UVI measurements at the tropical station (Paramaribo) on 28 July 2001. The solid line shows the clear sky UV-index parameterised as derived in this paper. The dotted line shows the parameterisation of Burrows et al. (1994).*

12 h UT. The visibility that day was between 30 and 40 km. During the day the Brewer performed 71 successful direct sun total ozone measurements, with an average value of 347 ± 5 Dobson Units. Figure 3 shows the 22 UVI values calculated from the spectral scans performed during the day. The curve shows the UVI calculations based on the parameterisation described in the previous section (solid line) and the parameterisation of Burrows et al. (1994) (dotted line). Notice the better performance of our parameterisation at SZA larger than 70°.

The second case presents the UVI measurements for Paramaribo on 28 July 2001. Although the day started as cloud-free, just after midday clouds formed, which is quite usual at this site. Some 40 direct sun total ozone measurements were performed during the day, showing an average total ozone value of 267 ± 2 Dobson units. The 22 UVI measurements are shown in Figure 4. Also shown are the UVI calculations based on both parameterisations. The newly derived parameterisation gives much higher UVI values for SZA < 30°, in accordance with the measurements.

As is clear from these results, the parameterisation of Burrows et al. (1994) remains valid for the range of SZA values for which it was intended. The virtue of this work is that it can be applied to the full range of SZA values.

6. Summary

The clear sky UV-index is expressed as a function of two predictable quantities, the Solar Zenith Angle and Total Ozone. A practical formula for forecasting the UVI is derived by combining equations (6) and (8). This formula is based on measurements at two stations, one in the mid-latitudes, and another in the tropics. The formula is computationally efficient, and can be used to calculate the clear-sky UV-index globally. We feel that because of the carefully selected functional dependence that is used, this function may also apply outside the range of ozone values that have been used for the fitting.

Both stations are located at low altitude. For sites at higher elevations, a correction for the increase of the UV-index with altitude (5% per kilometre) can be applied, as long as no snow cover is present. The presence of snow cover, especially in a mountainous region, makes an accurate UVI forecast more difficult.

Currently we are using the parameterisation described in this paper to make global UVI forecasts based on satellite ozone data. These forecasts are available at http://www.knmi.nl/gome_fd/.

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