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Dependence of ultraviolet (erythemal and total) radiation and CMF values on total and low cloud covers in Central Spain

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ABSTRACT

The cloudiness effect on solar ultraviolet radiation (UV) has been analyzed in this study. Measurements of erythemal and UV total radiations have been registered in Valladolid, Central Spain (lat. 41° 40′N, long. 4° 50′W and 840 m a.s.l.). A statistical analysis of cloudiness has been carried out resulting clear skies (0–2 oktas) the most frequent conditions under low cloud cover, while cloudy skies (6–7 oktas) are the prevailing under total cloud cover. Hence, the dependences of erythemal UV (UVER) and UV total (UVT) radiations and CMF values (on both ranges) on total and low cloud covers have been analyzed. In all cases, low clouds show higher attenuation than total cloud cover. Moreover, an empirical formula proposed by other authors for several Spanish cities is verified with very similar coefficients for Valladolid database. Finally, the dependence of the ratio between CMF values on UVER and UVT radiations on cloud cover and solar elevation angle is analyzed. As a result, UVER and UVT radiations are not affected by the clouds in the same way. Actually, for low solar elevation angles, UVER is not as attenuated as UVT radiation. However, for high ones under cloudy (6–7 oktas) and, particularly, overcast (8 oktas) conditions, UVER presents smaller CMF values and, therefore, a higher attenuation. Due to the different spectral ranges between erythemal and UV total radiations, the photon reflections above the cloud, the Rayleigh scattering and the interaction of UV radiation with atmospheric components like ozone could explain these effects.

1. Introduction

Solar ultraviolet (UV) radiation, 100–400 nm, represents only a low percentage of the total solar energy which reaches the Earth's surface. But UV is the most energetic radiation of the lower atmosphere which is able to break up the chemical bonds of various molecules (Koepke et al., 2002); therefore, it exerts a significant influence on the atmosphere and on living organisms (ICNIRP, 2004).

Overexposure to solar radiation is responsible for the majority of cases of sunburn, skin cancer, skin ageing, immunosuppression and some forms of eye cataracts (Fioletov et al., 2009); although there are beneficial health effects as vitamin D synthesis (Webb, 2006). The efficiency of UV radiation to produce erythema, or sunburn, is represented by an action spectrum standardized in 1987 by the Commission Internationale de l'Eclarage (CIE) (McKinley and Diffey, 1987).

The factors involved in the attenuation of UV radiation on the Earth's surface are solar elevation, cloudiness, ozone, aerosols, surface albedo and height of the measuring site (Koepke et al., 2002). Day-to-day changes of the radiation over the northern hemisphere midlatitudes are dominated by the cloud variability (Krzyscin et al., 2003). Therefore, this study is focused on the role that clouds play on the solar UV radiation levels on the Earth's surface. Since clouds are formed by water droplets or ice crystals, radiation is scattered when passing through them, resulting in extinction or in a diminished atmosphere transmissivity (Calbó et al., 2005). The effects of other factors, like ozone or aerosols, have been studied, among others, by di Sarra et al. (2002), Anton et al. (2008) and Bilbao and de Miguel (2009).

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The most challenging problem with clouds is their high microphysical and macrophysical variabilities, both, with respect to space and time (Koepke et al., 2002). The effects of clouds on UV radiation are usually expressed by the cloud modification factor (CMF) defined as the ratio between measured UV radiation in a cloudy sky and calculated radiation for a cloudless sky (Calbó et al., 2005). This factor provides a first distinction of cloud radiative effects using the available database (Foyo-Moreno et al., 2001) and has been introduced to reduce the effect of the most influential parameters such as ozone or solar elevation angle over UV radiation attenuated by clouds (Esteve et al., 2010).

In recent studies the influence of clouds on UV radiation has been analyzed. In a high-mountain area, Blumthaler et al. (1994) found that UV-A and UV-B radiation attenuations by clouds are influenced more by scattering than by ozone. To what extent cloudiness and ozone have an effect on the annual cycle on UV-B radiation was showed by Ilyas et al. (1999). The dependence of CMF in the UVT range on cloudiness has been analyzed in Valladolid, Spain by Mateos et al. (2009). A potential relationship was found between CMF and total cloud amount in a study about three Spanish cities (Alados-Arboledas et al., 2003). The dependence of UVER and CMF values on total and low cloud covers was studied in Valencia, Spain by Esteve et al. (2010). The use of CMF, derived from modification by cloud of the global broadband solar radiation, in order to evaluate the horizontal plane cataract effective UV radiation was studied, e.g., by Parisi et al. (2007). The UV radiation enhancement by clouds has been recently studied, among others, by Sabburg and Parisi (2006) and Krzyscin et al. (2003). The combination of radiative transfer model calculations and broadband and spectral irradiance measurements has been used to get to know the type of cloud producing a given attenuation in Córdoba, Argentina (López et al., 2009). The spectral dependency at 7 UV wavelengths was studied by Schwander et al. (2002) for several CMF parameterizations. This led to find out that the sensibility with respect to wavelength and solar zenith angle depends of each kind of parameterization.

The aim of this paper is to investigate the dependence of UV erythemal (UVER) and UV total (UVT) radiations on cloudiness. Hence, studies on total and low cloud covers and solar elevation angles have been carried out. Moreover, the cloud modification factor has been defined for both ranges and their dependence on cloudiness has also been analyzed.

The present study contributes to improve the knowledge of current UV levels in South-eastern Europe. For this reason, long temporal series of UVER and UVT radiation values have been shown. In the following sections, a description of the measurement station, the data series characteristics, the methodologies and the obtained results can be seen.

2. Site, instrumentation and methodology

The Research Centre of the Low Atmosphere (CIBA, lat. 41° 40′N, long. 4°50′W and 840 m a.s.l.), is located in a wide-open area (free of obstructions) close to Valladolid, Spain. The maximum temperatures occur in summer around 35 °C with clear skies, while the minimum temperatures in winter are about −7 °C. The typical rainfall amount along the year is about 580 mm. CIBA solar monitoring station contains a large number of radiometric and meteorological sensors; a more detailed description of each one was carried out by Bilbao et al. (2002).

Measurements of UVER radiation have been obtained by an UVB-1 YES pyranometer which has a spectral sensitivity close to the erythemal action spectrum. This pyranometer was calibrated in the National Institute for Aerospace Technology (INTA) in Spain. The calibration consisted of a measurement of the spectral response of the radiometer indoors and a comparison with a Brewer MKIII spectroradiometer outdoors (Vilaplana et al., 2006). The experimental uncertainty of this instrument is about 8–9% (Pearson et al., 2000). Measurements of 10-min UVER irradiance were analyzed during the period from July 2002 to December 2008.

An Eppley TUVR radiometer records horizontal ultraviolet total solar radiation (UVT, 290–385 nm). This instrument has been calibrated at Eppley Laboratories with an uncertainty of ~10%. Measurements of 10-min UVT irradiance were analyzed during the period from February 2001 to December 2008. For further details about UVT measurements see Bilbao et al. (2010). These radiometric sensors are connected to two CR23X Campbell Dataloggers which are programmed for registering measurements every 10 min integration time. The data quality control followed in this work was explained in detail in a previous paper (Bilbao et al., 2008), taking into account the detection limits of the sensor and comparing with the extraterrestrial values.

The cloud cover observed by the trained staff of Villanubla Airport (Valladolid) has been obtained from the Spanish Meteorological Agency (AEMet). In this area, the landscape is flat and the distance between this observatory and CIBA station is 10 km. Cloudiness (total and low cloud covers) was

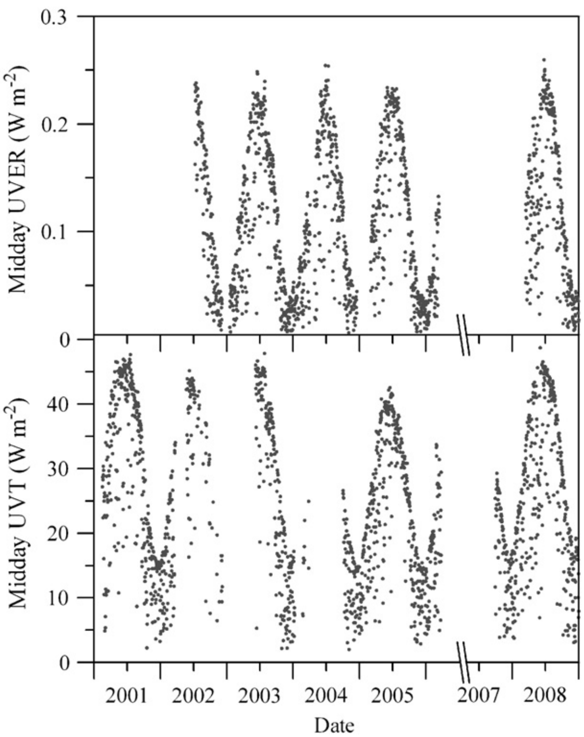

Fig. 1. Co-variability of midday UVER (up) and UVT (down) solar radiation (points) in Valladolid, Spain.

Table 1
Number of data in each category of cloud cover and solar elevation angle ($h_1 \geq 60°$, $40° < h_2 < 60°$ and $h_3 \leq 40°$).

Cloud cover (oktas)	Total			Low		
	h_1	h_2	h_3	h_1	h_2	h_3
1	46	29	24	35	19	5
2	32	28	22	10	15	8
3	26	21	23	9	6	10
4	20	30	29	5	9	17
5	25	21	37	12	7	18
6	32	47	44	15	19	16
7	42	56	90	7	22	46
8	13	22	100	7	7	62

recorded three times per day (7:00 h, 13:00 h and 18:00 h GMT) in oktas. In this study, only the cloudiness measured at 13:00 h GMT was used, because the maximum of solar radiation happens at this time. To separate the effect of low clouds, this cloud cover is only selected when there are no other types (i.e., medium or high ones). Therefore, in order to study the influence of total cloudiness on UVER and UVT radiation measurements, the average value of the 10-min data between 12:50 h and 13:10 h GMT was taken as representative of 13:00 h GMT. In this way, 1408 and 1685 values of UVER and UVT radiations were obtained, respectively. Fig. 1 shows the temporal evolution of the midday values of UVER and UVT radiations in Valladolid, Spain. The gaps represent the periods in which the sensors were damaged or in calibration campaigns.

In order to avoid effects due to the coincidence of different atmospheric conditions, only days with both measurements have been taken into account in the analysis. Then, these values of UVER and UVT at 13:00 h GMT were classified according to the cloud cover, in oktas, and to the solar elevation angle (h), using three intervals: a) $h \geq 60°$, b) $40° < h° < 60°$ and c) $h \leq 40°$. Table 1 shows the number of data in each category of cloud cover (total and low) and solar elevation angle.

The estimation of UVER and UVT radiations in cloudless skies has been carried out using the radiative transfer model TUV4.4 (Madronich, 1987). This model has free access by http://cprm.acd.ucar.edu/Models/TUV. The final setup used in the model was as follows: the integrated spectral ranges were erythemal and UV total (290–385 nm); the wavelength grid was built by 1 nm intervals; the surface albedo was assumed to be Lambertian with a value of 0.03; the extraterrestrial irradiance values were taken from Van Hoosier et al. (1987) and Neckel and Labs (1984). Profiles of temperature, air density and ozone were obtained from standard atmosphere in USA (45°N) in 1976. Daily total ozone column values were provided by the National Aeronautics and Space Administration (NASA) by Total Ozone Mapping Spectrometer (TOMS) and Ozone Monitoring Instrument (OMI) sensors (free access by http://macuv.gsfc.nasa.gov/). Pressure on surface was fixed at 920 mb. For the aerosol optical depth at 550 nm, the monthly averages measured by AERONET network are used. On the other hand, O_3, SO_2 and NO_2 have not been considered due to the low levels of tropospheric pollutants at CIBA station. Therefore, 10-min data of UVER and UVT radiations in cloudless conditions were calculated by 8-stream discrete ordinate method (DISORT), a sufficient number when calculating integrated radiation quantities such as irradiance (Meloni et al., 2006). These simulated values were used to evaluate 10-min CMF values on UVER and UVT radiations.

3. Results and discussion

3.1. Statistical analysis of cloudiness in Valladolid, Spain

First, a statistical analysis of cloudiness (total and low cloud covers) at 13:00 h GMT was carried out in Valladolid, Spain. Fig. 2 shows the frequency histograms of total (Fig. 2a) and low (Fig. 2b) cloud covers in Valladolid. According to the World Meteorological Organization (WMO) classification, http://worldweather.wmo.int/oktas.htm, 30% of the cases correspond to a situation of clear skies (0–2 oktas), 24% of the cases are partially cloudy skies (3–5 oktas), 32% of the cases are cloudy skies (6–7 oktas) and 14% correspond to overcast skies (8 oktas) when total cloud cover is analyzed. These figures change to 41, 20, 24 and 15%, respectively, when only low cloud cover is observed. With these values, the cloudiness conditions in Valladolid are, mainly, clear or cloudy skies. In low cloud cover, clear sky conditions are predominant, while cloudy sky conditions are the majority in total cloud cover. In a study of a Mediterranean city, Esteve et al. (2010) found more cases of

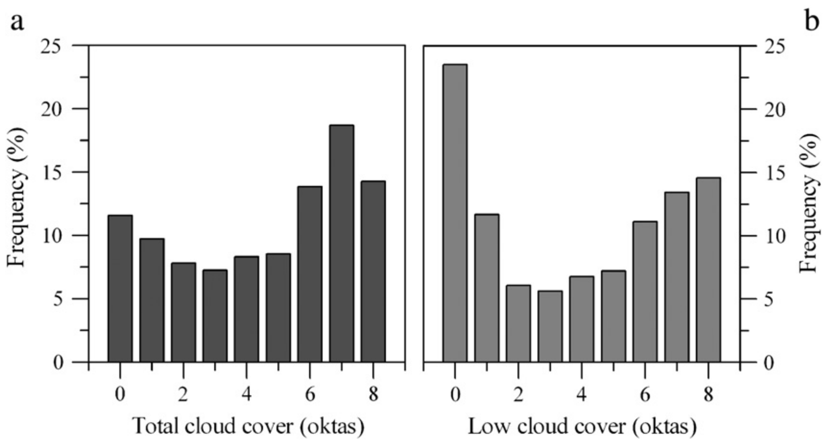

Fig. 2. Frequency histograms of total (a) and low (b) cloud covers at 13:00 h GMT in Valladolid, Spain.

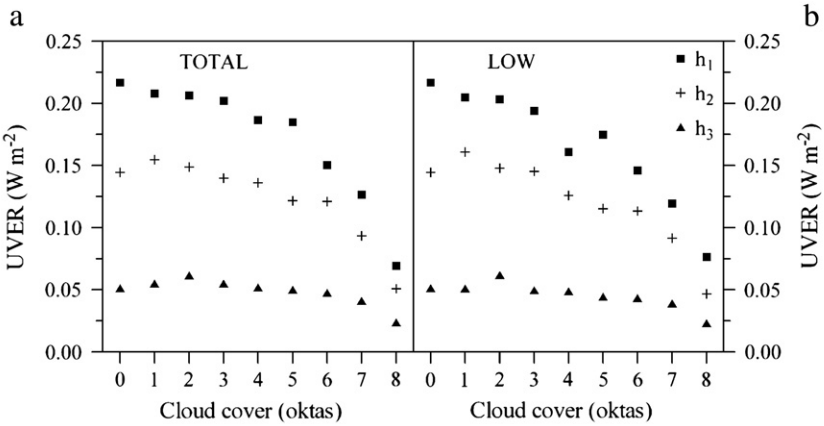

Fig. 3. Dependence of average value at 13:00 h GMT of UVER on total (a) and low (b) cloud covers for three intervals of solar elevation angle: $h_1 \geq 60°$, $40° < h_2 < 60°$ and $h_3 \leq 40°$.

clear or partially cloudy sky conditions than in this study (Mediterranean-continental climate). This fact corroborates the presence of different climates in the Iberian Peninsula.

Although in this work the dependence of the UV radiation on type of clouds is not analyzed, with respect to the type of low clouds, 80% of the cases are cumulus and stratocumulus (50 and 30%, respectively). It is worth mentioning that for both medium and high clouds, most of them (>60%) are altocumulus and cirrus, respectively.

3.2. Dependence of UVER and UVT radiations on cloudiness

Figs. 3 and 4 show the dependence of the midday values of UVER and UVT radiations on cloudiness (total and low) for each amount of cloud cover. Moreover, to study the effect of the solar elevation angle (h), the irradiance values are classified into 3 groups mentioned in Section 2: a) $h \geq 60°$, b) $40° < h < 60°$ and c) $h \leq 40°$. Therefore, these figures present the dependence on total (Figs. 3a and 4a) and low (Figs. 3b and 4b) cloud cover for each interval of h. The UV radiation decreases as cloudiness increases for all elevation angles and for both cloud covers, and this reduction rises with h. The range of the lowest solar elevation is the least affected by the presence of clouds. Under total cloudiness, from clear (0–2 oktas) to cloudy (6–7 oktas) skies, UVER radiation falls between 20 and 35% in the three ranges of solar elevation angle, while under low cloudiness, this variation is between 30 and 35%. These percentages are lower than the obtained by Esteve et al. (2010), but they used hourly averages. These values change, when UVT radiation is analyzed, to 20–25% and 23–30% for total and low cloudiness, respectively. As a consequence, this fact seems to indicate that low clouds present higher attenuation than total cloud cover.

Under clear or cloudy skies (from 1 to 4–5 oktas), a smooth trend is observed between UVER and UVT radiations and both cloud covers; but this behaviour changes when the cloud cover rises.

It is important to note that in this paper the role of the cloud optical thickness has not been analyzed and, it may have an important effect on these results.

3.3. Dependence of CMF on cloudiness

CMF values for UVER and UVT radiations were calculated as mentioned in Section 2. As the average of irradiance was

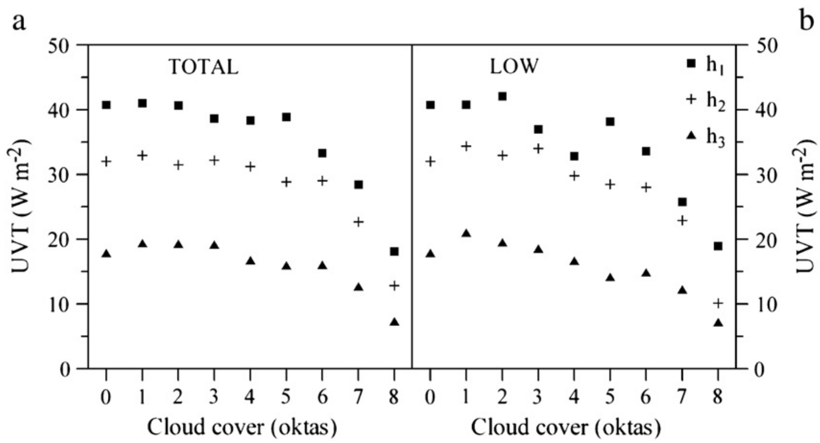

Fig. 4. Dependence of average value at 13:00 h GMT of UVT radiation on total (a) and low (b) cloud covers for three intervals of solar elevation angle: $h_1 \geq 60°$, $40° < h_2 < 60°$ and $h_3 \leq 40°$.

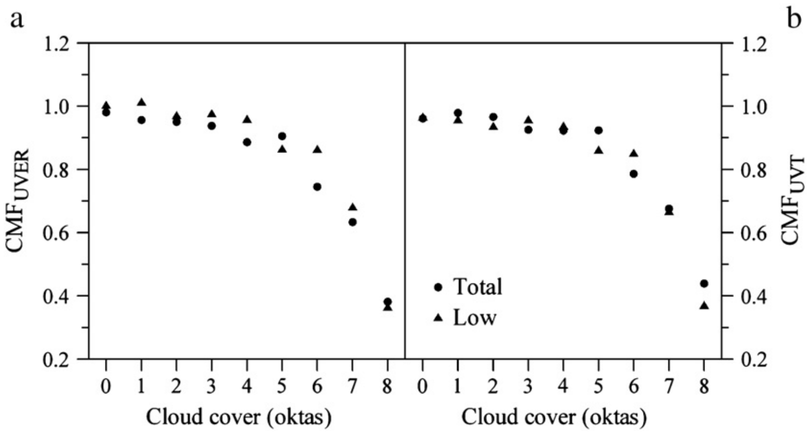

Fig. 5. Dependence of CMF average values at 13:00 h on total and low cloud covers: UVER (a) and UVT (b) ranges.

taken as representative at 13:00 h GMT, only the 10-min model estimation at 13:00 h GMT is used to evaluate CMF. Fig. 5 shows the dependence of CMF on total and low cloud covers for all solar elevation angles. As expected, CMF values present a decreasing trend with cloudiness. CMF values on UVER and UVT radiations seem to have a similar trend. The values of CMF under total cloud cover are slightly higher than the ones under low clouds.

Alados-Arboledas et al. (2003) proposed the following empirical formula for the UVER range for three Spanish cities (Madrid, Murcia and Zaragoza):

$$\mathrm{CMF} = 1\text{–}A(\mathrm{cc}/8)^{B} \tag{1}$$

where cc is the total cloud cover and A and B, the empirical coefficients whose values are given in Table 2. The accuracy of the empirical formula is evaluated by the main error statistical indexes: mean bias error (MBE), mean absolute bias error (MABE) and root-mean square error (RMSE) following Miguel et al. (2001). The results are shown in Table 2.

Excellent results are achieved both for UVER and UVT radiations showing, e.g., RMSE values always lower than 5%; therefore, the CMF dependence on total cloud cover is similar for both spectral ranges and for these Spanish cities. This fact is of great relevance because the Valladolid database on which this study rests on is bigger than the one used by Alados-Arboledas et al. (2003). Then, the empirical formula (1) was applied to fit this expression for total and low cloud covers and for UVER and UVT radiations in Valladolid. The obtained coefficients are shown in Table 3. As it can be seen, for both ranges under total cloud cover, the coefficients are very similar; but they are different with respect to the values under low cloud cover. So, low clouds present higher attenuation than total cloud cover; i.e., the same result found in Section 3.2 and by Alados-Arboledas et al. (2003). But under overcast skies (8 oktas), this fact changes and the function for low cloud cover shows smaller values than the one for total cloud cover.

Another variable is evaluated to study the difference of CMF values on both UV ranges, which expresses the ratio between the CMF on UVER and UVT radiations:

$$R = \mathrm{CMF}_{\mathrm{UVER}} / \mathrm{CMF}_{\mathrm{UVT}}. \tag{2}$$

The values of this variable have been classified into the three solar elevation angle categories mentioned above. So, the dependence of R on cloud cover and elevation angle is shown in Fig. 6.

A clear dependence on solar elevation angle appears, however, no differences between total (Fig. 6a) and low (Fig. 6b) cloud covers are appreciated. By definition, when R shows values over the unit, CMF values on UVER are higher than the ones on UVT radiation, i.e., the clouds reduce UVT radiation more strongly than UVER range. This situation occurs for low solar elevation angles when, moreover, an increasing trend with cloudiness is observed. To explain this experimental effect, Kylling et al. (1997) found that the reflections upwards by the cloud and the dispersions downwards again by the atmosphere (Rayleigh scattering) above the cloud produce shorter wavelengths that make it through the cloud more effectively than the longer wavelengths in the UV range (Lindfors and Arola, 2008). However, for high solar elevation angles, the effect

Table 2
Comparison of statistical estimators of the empirical formula by Alados-Arboledas et al. (2003) with the Valladolid database.

City	A	B	UVER			UVT		
			MBE (%)	MABE (%)	RMSE (%)	MBE (%)	MABE (%)	RMSE (%)
Madrid	0.60	4.10	0.40	2.36	2.50	1.95	2.88	3.20
Murcia	0.51	2.80	−0.74	3.85	4.71	0.79	3.66	5.09
Zaragoza	0.55	4.30	2.45	2.45	2.84	4.03	4.03	4.41

Table 3
Fitting coefficients for the CMF (Eq. (1)) on UVER and UVT radiations and total and low cloud covers.

	UVER		UVT	
	Total cloud cover	Low cloud cover	Total cloud cover	Low cloud cover
A	0.57 ± 0.02	0.55 ± 0.03	0.59 ± 0.03	0.58 ± 0.04
B	4.03 ± 0.27	3.20 ± 0.41	3.83 ± 0.37	3.10 ± 0.40
r^2	0.99	0.96	0.98	0.96
RMSE	2.20%	4.30%	3.00%	4.40%
MBE	1.17%	1.79%	1.50%	1.20%

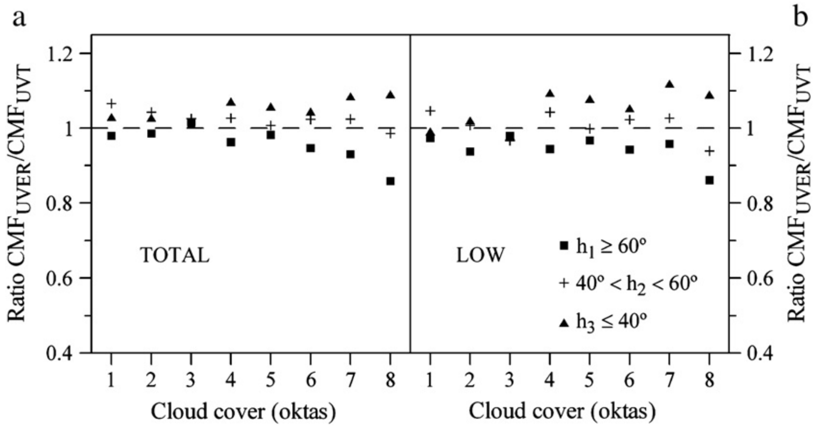

Fig. 6. Dependence of the ratio CMF_{UVER}/CMF_{UVT} on total and low cloud covers for three intervals of solar elevation angle: $h_1 \geq 60°$, $40° < h_2 < 60°$ and $h_3 \leq 40°$. The dashed lines mean that the ratio is equal to 1.

changes showing a decreasing trend and values of the ratio below the unit, which means that the UVER radiation is more attenuated than the UVT one. This fact could be explained by the role of the UV diffuse component. Under cloudy conditions, its role is predominant (e.g., direct component under overcast skies nearly reaches zero) and its interaction with the atmospheric constituents, like ozone, could produce higher attenuation in the UVER range. Actually, the measurements of UVT radiation, 290–385 nm, are less affected by ozone because the main part of the instrument spectral response is on the UV-A range.

4. Conclusions

In this paper, the influence of cloudiness on UV radiation has been investigated. A statistical analysis in Valladolid has been carried out in order to show the likely occurrence of clear and cloudy skies for both total and low cloud covers. When the midday values of UVER and UVT radiations are analyzed, the low clouds present more attenuation than the total cloud cover. The CMF values are assessed with radiative transfer simulations and their dependence on cloud cover is studied. They again show that the values under total cloud cover are slightly higher than the ones under low cloud cover. An empirical formula proposed for other Spanish cities by Alados-Arboledas et al. (2003) is verified with the Valladolid database and, the obtained coefficients are very similar to the other ones proposed for cities like Madrid and Zaragoza. However, this relationship between CMF and total cloud cover, which is valid for UVER and UVT radiations, presents different coefficients when it is based on low cloud cover. The obtained results lead to a higher absorption under low clouds except in the case of 8 oktas for which the total cloud cover produces the lowest values of CMF.

Finally, the ratio between CMF values on UVER and UVT radiations is studied. The dependence of this variable on total and low cloud covers and solar elevation angle shows that UVER and UVT radiations are not attenuated in the same way by the presence of clouds. Particularly, for low solar elevation angles, UVER radiation is less attenuated, as expected by the results found, e.g. by Kylling et al. (1997). However, for high ones, the interaction between the diffuse component and the atmospheric constituents, like ozone, causes higher attenuation in the erythemal range.

These results are interesting for climatology, radiative transfer and biophysical studies, among others; hence, the role of cloudiness on solar radiation still remains open.

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