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GROUND BASED ULTRAVIOLET (290–385 nm) AND BROADBAND SOLAR RADIATION MEASUREMENTS IN SOUTH-EASTERN SPAIN

I. FOYO-MORENO, J. VIDA and L. ALADOS-ARBOLEDAS*
Grupo de Física de la Atmósfera, Departamento de Física Aplicada, Universidad de Granada, Granada, Spain

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ABSTRACT

Presented here is the first analysis of hourly solar ultraviolet irradiance (290–385 nm) and broadband global irradiance data, registered in a radiometric station located in the outskirts of Granada (37.18°N, 3.58°W, 660 m a.m.s.l.), an inland location in south-eastern Spain, during a 2-year period. According to the prevailing cloudless conditions, the results show that the highest UV radiation levels are received in June or July and the lowest in December. Hourly monthly means of the ratio UV to broadband solar radiation covers a range from a minimum of *ca.* 3% to a maximum of 5%. The higher values of this ratio are associated to cloudy situations. In this way for 1994, the lowest values of this ratio are encountered in December, and the highest value appears in May, associated with a higher frequency of cloudy days. The study of the ratio UV to global radiation hourly monthly means reveals a clear effect of the optical air mass and of the cloud cover. It is found that, the UV to broadband global radiation ratio increases with decreasing optical air mass and increasing cloud cover. © 1998 Royal Meteorological Society.

KEY WORDS: ultraviolet solar irradiance; broadband solar irradiance; hourly values; optical air mass; cloud radiative effect

1. INTRODUCTION

The study of solar ultraviolet radiation has received considerable attention in the past few years (Al-Aruri *et al.*, 1988; Al-Aruri, 1990; Elhadidy *et al.*, 1990; Feister and Grasnick, 1992; Khogali and Al-Bar, 1992; Sadler, 1992; Martinez-Lozano *et al.*, 1994, 1996) because of its biological, ecological, and physical effects produced by short-wave radiation received at the surface of the earth.

Solar UV radiation is usually divided into three bands (CIE, 1987): UV-C (100–280 nm) which is completely absorbed by stratospheric ozone; UV-B (280–315 nm) which is only partially absorbed or scattered in the atmosphere and UV-A (315–400 nm) which makes up most of the UV radiation received at the earth's surface. Considering the solar spectral irradiance (Fröhlich and London, 1986), in outer space UV-B and UV-A bands account for only *ca.* 7.45% of the total solar radiation.

The stratospheric ozone forms a shield around the globe protecting the biosphere from the deadly ultraviolet radiation coming from the sun. A slight decrease in the stratospheric ozone leads to an increase in the UV-B reaching the earth. UV radiation data are of particular interest because such radiation is energetic enough to break apart several biological molecules, including DNA (Al-Aruri, 1990). An increase in UV radiation affects human health (Horneck, 1995).

There are wide spatial and temporal variations in the UV irradiance at the surface of the earth depending on latitude, solar elevation and atmospheric and local conditions. Despite the recognised

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* Correspondence to: Departamento de Física Aplicada, Facultad de Ciencias, Universidad de Granada 18071, Granada, Spain; tel.: + 34 9 58244024; fax: + 34 9 58243213; e-mail: alados@goliat.ugr.es

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importance of ultraviolet radiation, its measurement has received little emphasis and the observational data available are few and sporadic.

This paper investigates aspects of the temporal variation of solar UV (UVA + UVB) recorded in a radiometric station for a 2-year period. The concurrent registrations of UV and global solar irradiance have been used to study the relationships between both radiometric quantities.

The seasonal behaviour of the UV radiometric flux has been analysed by studying the daily pattern of this flux on a monthly basis. Because of the availability of solar broadband radiometric flux data, the ratio UV to broadband global radiation was also examined on an hourly basis. The seasonal and daily pattern of this ratio is included in the study. Additionally, a contribution is made to the identification of the factors that may control the variability of the UV to broadband global radiation ratio. This result offers the possibility of estimating the UV solar radiation (UVA + UVB) incident on a horizontal surface from the global irradiance measurements received on that surface.

2. DATA AND MEASUREMENTS

Broadband solar irradiance (0.3–3 μm), global and diffuse, ultraviolet global irradiance, photosynthetically active irradiance (400–700 nm), longwave atmospheric irradiance (4–100 μm) and other meteorological variables have been continuously registered, since the end of 1993, in a radiometric station installed by the University of Granada and the Spanish national meteorological institute in the meteorological office of the Armilla air force base (37.18°N, 3.58°W, 660 m a.m.s.l.), an inland location in south-eastern Spain. The measurements are taken every 5 s and registered as 1-min mean values. Solar global irradiance was measured using a Kipp and Zonen model CM-11, and a second Kipp and Zonen model CM-11 with a polar axis shadowband was used to measure solar diffuse irradiance. An Eppley TUVR radiometer was used to measure ultraviolet irradiance (290–385 nm) on a horizontal surface. Finally, air temperature and relative humidity at 1.5 m are also recorded. The diffuse irradiance measurements obtained by means of the shadowed pyranometer have been corrected following the method proposed by Battles *et al.* (1995).

From this data base, hourly values have been generated covering the period from January 1994 to December 1995, which is a guarantee that a wide range of seasonal conditions and solar elevation angles are covered and included among the samples that have been taken.

It is important to point out that there are significant differences in temporal and cosine response between the radiometers used for the measurements of UV and broadband solar irradiance. Consequently hourly values have been computed, in order to reduce the temporal effects that could be introduced in the study of the ratio UV radiation to broadband solar radiation. These undesirable effects can reach quite a significant level, especially under highly changing conditions, which are usually associated with broken cloud fields. On the other hand, differences in the cosine response impose a threshold for the solar elevation to be considered in the study of UV/G ratio hourly values. Therefore, hourly values for this ratio corresponding to solar elevation angles under 10° have been rejected in the data filtering procedure.

Calibration checks have been performed every year. The decay of the TUVR radiometer constant has been evaluated by means of a field comparison with measurements performed by a side by side operating field spectroradiometer (LI-1800, LI-COR). In this way a 2% decrease per year has been established. Measurements of solar global and diffuse irradiance have an estimated experimental error of *ca.* 2–3%. As indicated by several authors (Riordan *et al.*, 1990; Mehos *et al.*, 1991), the relative error of the TUVR radiometer can be as high as 15%, which is not in accordance with the expectation of the manufacturer (5%). Considering the marked thermal dependence of the TUVR detector, we have used the air temperature measurements in order to correct this effect. According to the manufacturer we have used a thermal coefficient of -0.2% per degree deviation between -40 and $+5$°C and -0.5% between $+25$ and 50°C.

3. RESULTS AND DISCUSSION

The present study analyses the UV irradiance (290–385 nm) data recorded at Granada. Hourly values of the UV irradiance and the ratio between ultraviolet irradiance and global irradiance (UV/G) have been studied . In Figures 1 and 2, is shown that the monthly average global ultraviolet radiation flux for each hour of the day and each month during 1994 and 1995. These plots are a good illustration of the type of variation which can take place through a year. The maximum UV global irradiance hourly values occur at solar noon and the minimum in the extreme hours (the beginning and the end of the day). In 1994, the highest maximum takes place in June with a value of 39.0 W/m^2 and the lowest in December with a value of 14.7 W/m^2 (at solar noon). In 1995, the maximum takes place in July (41.1 W/m^2) and the lowest maximum in December as well (13.0 W/m^2).

From Figures 1 and 2 we can also see a high symmetry in the distribution over the year with maximum values at solar noon. These results are similar every month, even though the highest values occur in the summer while the winter months gives the lowest values. The seasonal variations are a result of the longer path of radiation with greater solar zenith angles. For every hour of the day, the highest values occur in June/July and the lowest in December. The plots show a similar behaviour in spring/summer and autumn/winter months. This result has also been obtained by Martinez-Lozano *et al.* (1996) in Valencia (Spain), which is explained by the authors from the seasonal symmetry in relation to the summer and winter solstices.

To investigate the proportion that the ultraviolet irradiance represents over the solar broadband irradiance, Figures 3a, 3b, 4a and 4b, corresponding to 1994 and 1995, respectively, show the patterns of the monthly hourly UV/G ratios. The study of these graphs reveals that there are months bearing UV/G

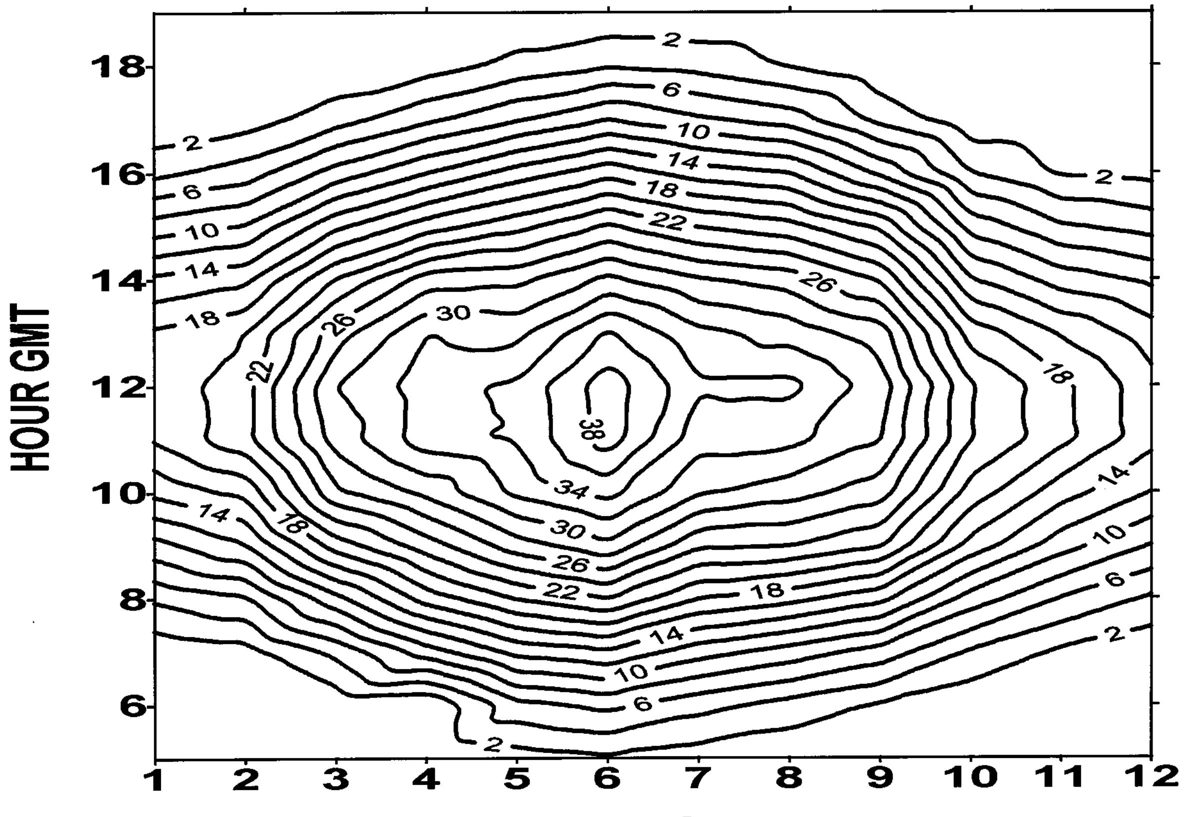

Figure 1. Monthly mean hourly global UV irradiance (W/m^2) for 1994

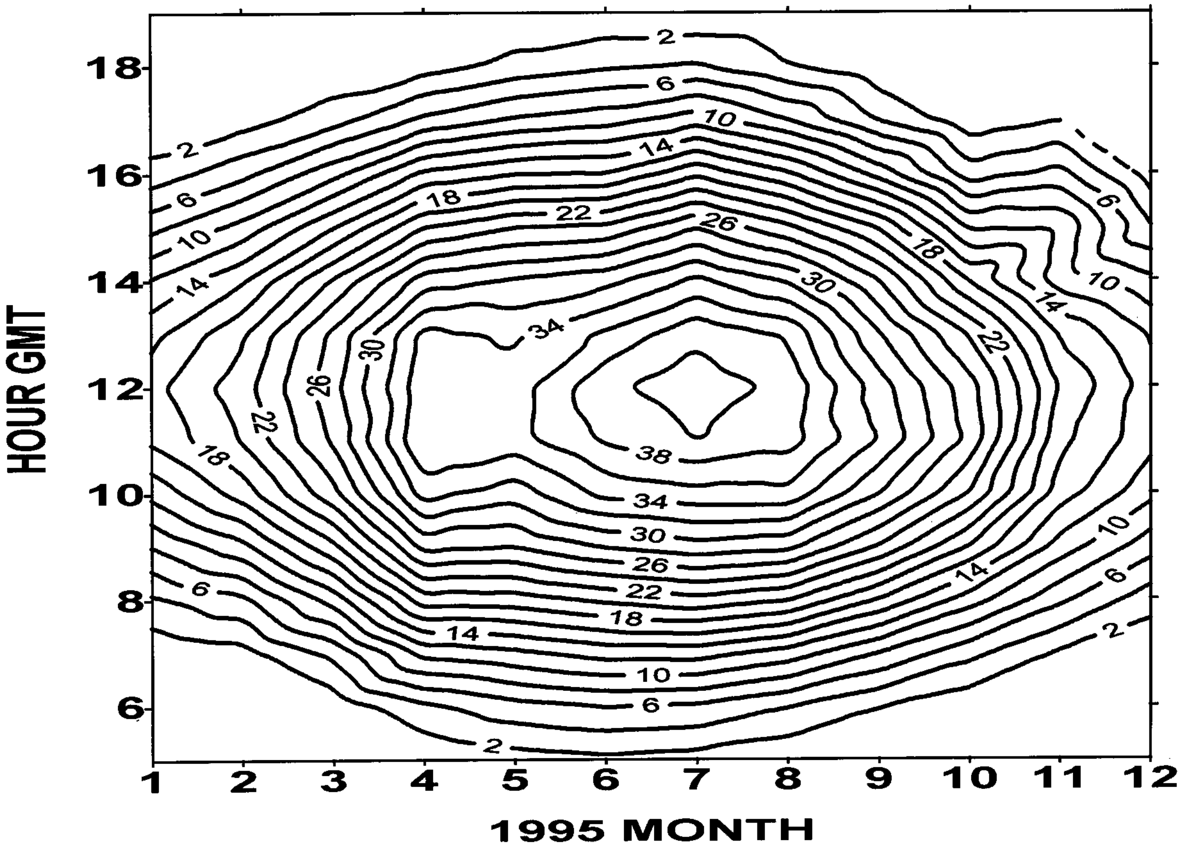

Figure 2. Monthly mean hourly global UV irradiance (W/m^2) for 1995

ratio patterns closely associated to the pattern of the cosine of the solar zenith angle, as opposed to others that show more erratic behaviour. In order to study these phenomena, an analysis of the clearness index, k_t and the diffuse fraction k was conducted. The variable k_t is defined as the ratio of the global irradiance

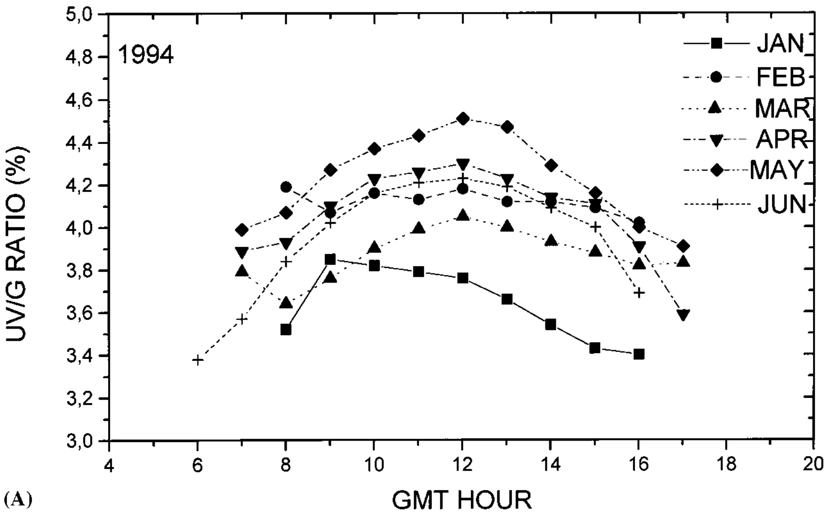

Figure 3a. Hourly monthly average of the ratio UV to broadband global irradiance (%) for the first half of 1994

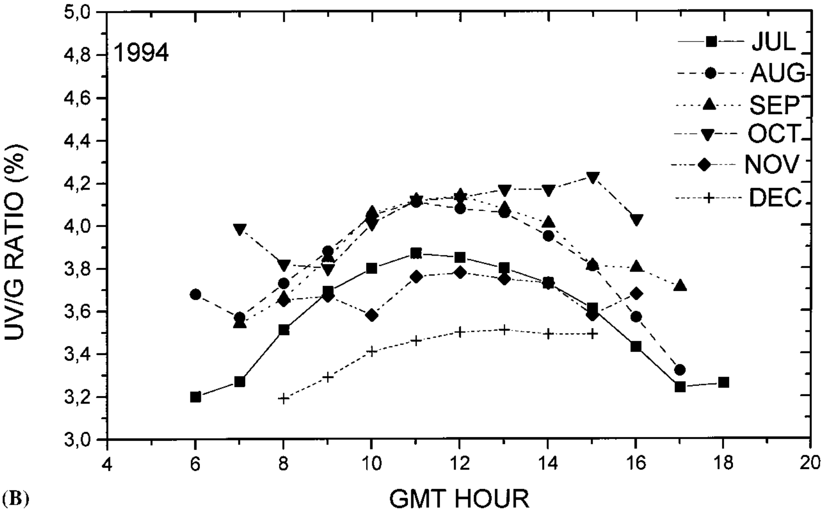

Figure 3b. Hourly monthly average of the ratio UV to broadband global irradiance (%) for the second half of 1994

to the extraterrestrial irradiance, both on a horizontal surface; k is defined as the ratio of the diffuse irradiance to the global irradiance, both on a horizontal surface. A high k value and low k_t value indicates a very cloudy sky and a low k value together with a high k_t value is associated with cloudless sky conditions, intermediate values for both parameters corresponding to partially cloudy conditions. In this study, the cloud cover is taken into account by its effects on the k_t, k indices. In this way, cloud information regarding type and coverage is not considered, but the radiative effects on the broadband solar radiation is accounted for. In Table I, the average values for the two parameters for 1994 and 1995 are shown, respectively. It is clear that those months displaying erratic behaviour in the UV/G ratio pattern are associated with cloudy conditions.

It can be observed from Figures 3a and 3b that the lowest values for the ratio UV/G occur in December and the highest in May. In Table I it can be seen that October 1994 presents the highest k value, followed by February and May. This means that there is a higher frequency of cloudy days which, together with lower optical air mass, contributes to higher proportion of UV with respect to global irradiance. If May

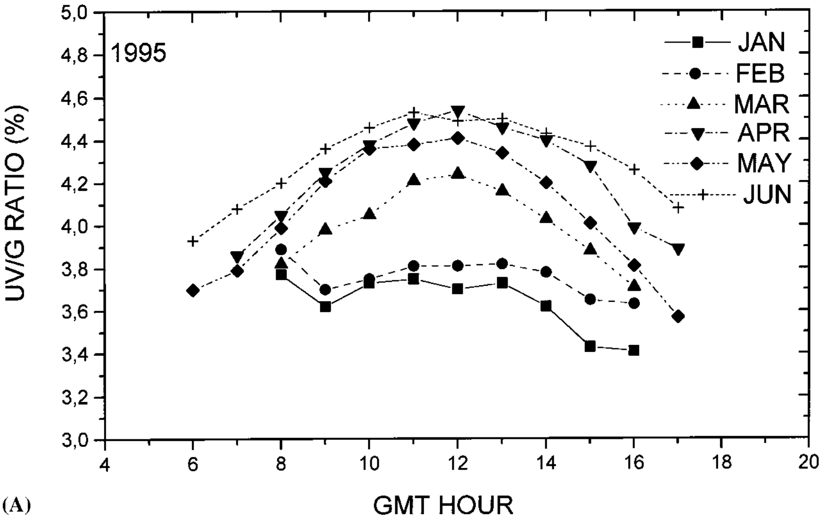

Figure 4a. Hourly monthly average of the ratio UV to broadband global irradiance (%) for the first half of 1995

Table I. Monthly average values for k and k_t during 1994 and 1995

Year	Indices	January	February	March	April	May	June	July	August	September	October	November	December
1994	k_t	0.63	0.54	0.62	0.60	0.57	0.66	0.63	0.62	0.63	0.51	0.57	0.58
	k	0.33	0.52	0.43	0.43	0.52	0.33	0.43	0.35	0.32	0.59	0.41	0.43
1995	k_t	0.48	0.50	0.51	0.55	0.54	0.52	0.58	0.56	0.53	0.50	0.40	0.32
	k	0.42	0.48	0.44	0.46	0.46	0.50	0.39	0.36	0.38	0.47	0.63	0.75

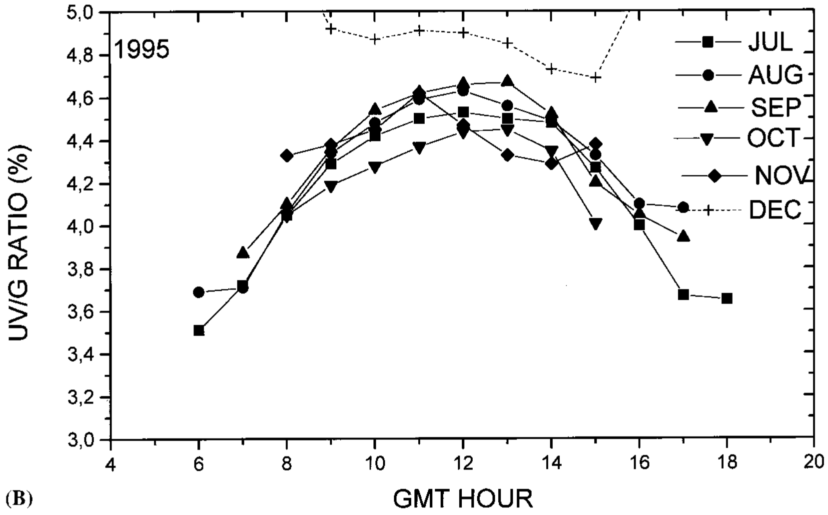

Figure 4b. Hourly monthly average of the ratio UV to broadband global irradiance (%) for the second half of 1995

and June in 1994 are compared, two similar months as far as optical air mass is concerned (Figure 5), we can see that the *k* index hourly values in May are higher than in June for every hour of the day. It can be observed that minimum values occur in the central hours, with a minimum of *ca.* 0.4 for May and 0.2 for June, thus highlighting the presumed importance of cloudiness.

Figures 4a and 4b show these results for the second year of the study. In 1995, the highest UV/G ratio corresponds to December instead of July. The lowest ratio occurs in January. From Figure 6 it can be observed that December is the cloudiest month in high contrast to the rest of the year (except November closely following December).

The previous analysis has shown that under cloudless conditions the UV/G ratio daily pattern closely follows the pattern of the cosine of the zenith angle. That is, under cloudless conditions the optical air mass seems to be the parameter with more influence. On the other hand, it has also proven that clouds substantially modify the UV/G ratio. Thus, the maximum encountered for December 1995 could be explained by the fact that clouds present higher transmittance for the UV spectral range. This is due to

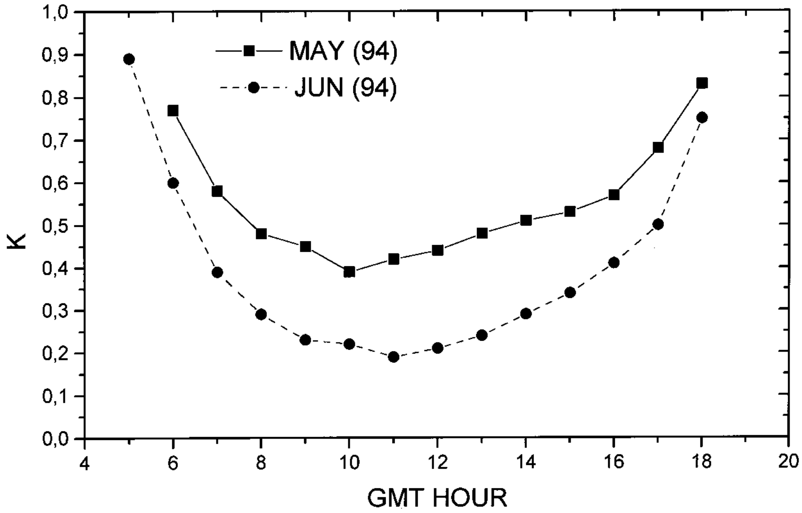

Figure 5. Monthly mean hourly diffuse fraction (*k*) for May and June in 1994

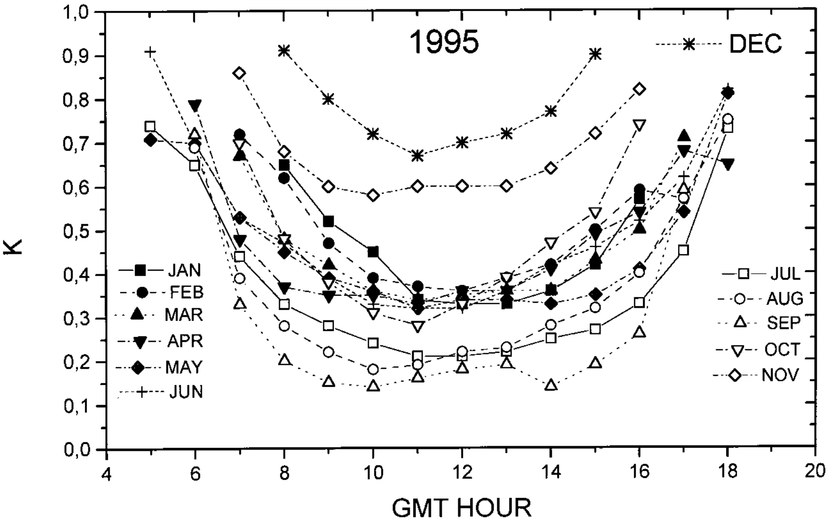

Figure 6. Monthly mean hourly diffuse fraction (k) in 1995

the fact that absorption by water vapour is much more acute in the near infrared region that in the shorter wavelengths (Lenoble, 1993). Different authors have suggested that for clear sky conditions, the proportion of UV to global radiation is generally smaller, as opposed to that associated with cloudy and overcast conditions (Elhadidy *et al.*, 1990; Ambach *et al.*, 1991; Feister and Grasnick, 1992; Sadler, 1992). Feister and Grasnick (1992) have evidenced the influence of clouds over the UV/G ratio at Postdam. In their study, typical values of UV/G at Postdam were 3–4%; with an overcast sky these ratios can increase up to 5–6%. The presence of clouds proportionately reduces the horizontal global solar irradiance more than they reduce UV global irradiance.

If we compare the same month (December) for 1994 and 1995 (Figures 3b and 4), with different values for indices k_t and k (Table I) and an equivalent optical air mass, it can be observed that an increase in cloudiness (December 1995 is more cloudy than 1994 on average, Table I) leads to an important increase in UV/G ratio from *ca.* 3 to 5%. On the other hand, observing Figure 3a and comparing two months (January and June) with a different optical air mass and similar sky conditions (prevailing cloudless conditions on average, see Table I), it becomes apparent that this difference also leads to an increase in UV/G ratio, but not as pronounced as before. In addition, the pattern followed by June, the month displaying the greatest optical air mass variability, shows an UV/G ratio range of *ca.* 3.5–4.2%. In this way, it seems evident that the most influencing factor in UV/G ratio change is cloudiness.

Atmospheric total ozone, which is on average higher in winter/spring than in summer/autumn, could represent an additional factor influencing in UV/G ratio (Feister and Grasnick, 1992) causing the ratio to hold a smaller value in winter/spring. However, this factor does not provoke much of a difference in this type of measurement, because the presence of ozone has an effect mainly on UVB radiation, whereas 95% of the irradiance measured by the TUVR consists of UVA (Martinez-Lozano *et al.*, 1996). This implies that the results for one band of the UV spectrum can not be related to the rest of the bands (Feister and Grasnick, 1992).

In any case, it is concluded on the basis of this study that the main factors to take into account are the optical air mass and the cloud cover conditions, as ozone absorption is only responsible for 2–3% of solar radiation's attenuation in the UVB region.

A comparison of our results for the ratio UV radiation to broadband global radiation values with those at Kuwait 29.3°N (Al-Aruri *et al.*, 1988), Dhahran 26.5°N (Elhadidy *et al.*, 1990) and Makkah 21.5°N (Khogali and Al-Bar, 1992) shows that they lie in the same wide range of *ca.* 3–5%. At Dhahran only, the ratio is almost constant due to the characteristics of its lower optical air mass (position of the sun); there is a high persistence of dusty conditions, thus relatively reducing the UV radiation more than the

Table II. Statistical parameters of the hourly ultraviolet irradiance (W/m^2) for June, 1994

h	N	Ave	SD	Md	Mo	Min	Ma	Q_-	Q_+	Ske	Cur	CV (%)
0500–0600	30	1.7	0.2	1.8	1.7	1.1	2.0	1.6	1.9	−1.4	1.6	13
0600–0700	30	6.6	0.8	6.8	6.8	3.8	7.6	6.3	7.1	−1.9	4.1	13
0700–0800	30	13.7	1.4	14.2	14.0	9.8	15.6	13.2	14.6	−1.6	2.5	10
0800–0900	30	21.9	2.1	22.4	22.2	15.3	24.5	20.9	23.4	−1.6	3.1	9
0900–1000	30	29.4	2.5	29.8	29.8	21.8	32.4	28.0	31.3	−1.4	2.4	8
1000–1100	30	34.6	4.3	35.8	35.6	20.5	38.8	34.4	37.3	−2.1	4.3	13
1100–1200	30	38.8	2.9	39.0	38.8	29.7	42.7	38.1	40.8	−1.5	2.6	8
1200–1300	30	39.0	4.8	40.2	40.1	19.8	43.3	38.3	41.7	−2.9	9.1	12
1300–1400	30	36.0	6.3	38.1	37.9	11.0	41.0	35.9	39.5	−2.8	−8.9	17
1400–1500	30	30.4	7.5	33.4	33.1	6.8	35.7	31.0	34.8	−2.2	3.9	25
1500–1600	30	24.2	6.7	26.6	26.4	1.6	28.4	24.4	27.8	−2.6	6.3	28
1600–1700	30	17.2	3.4	18.6	18.4	3.5	19.9	16.0	19.4	−2.5	7.9	20
1700–1800	30	9.9	1.8	10.6	10.3	2.4	11.5	9.4	11.0	−2.7	9.2	19
1800–1900	30	3.8	0.7	4.0	4.0	1.3	4.6	3.5	4.3	−2.0	5.0	18
1900–2000	29	0.4	0.1	0.4	0.4	0.3	0.6	0.4	0.5	−0.4	−1.3	22

broadband radiation, and resulting in a low and almost constant value of the ratio. At the rest of the localities the ratio shows strong variations throughout the year. The associated patterns vary from place-to-place because of different local climatological conditions, and from year-to-year, revealing the great influence of simple events. This could be considered as an argument against the suitability of using single estimation models of UV radiation based on broadband global radiation measurements, considering the absence of universality in their formulation. Clearly, the appropriate knowledge of UV radiation at a location requires direct measurements or alternatively the use of models that allow for all the important factors influencing this radiative flux.

Also carried out was a statistical study of the UV global irradiance, computing the most representative statistical indices for each hour of the day for all the months studied. This work has been carried out for the entire database and as an example of the behaviour for the 2 years, Tables II and III present these results corresponding to June. These indices are: arithmetic mean (Ave), standard deviation (S.D.), median (Md), mode (Mo), minimum (Min), maximum (Ma), inferior and superior quartile (Q_- and Q_+, respectively), skewness (Ske), kurtosis (Kur) and the variation coefficient (CV) defined as the ratio between S.D. and the arithmetic mean (CV = S.D./Ave).

Table III. Statistical parameters of the hourly ultraviolet irradiance (W/m^2) for June 1995

h	N	Ave	S.D.	Md	Mo	Min	Max	Q_-	Q_+	Ske	Kur	CV (%)
0500–0600	30	1.6	0.5	1.8	1.8	0.3	2.0	1.4	1.9	−1.6	1.5	30
0600–0700	30	6.1	1.7	7.1	6.8	1.7	7.6	5.2	7.3	−1.5	1.0	28
0700–0800	30	12.9	3.5	14.7	14.4	4.4	15.8	12.1	15.0	−1.5	0.9	27
0800–0900	30	20.5	5.3	22.9	22.8	7.1	24.7	18.7	24.0	−1.6	1.4	26
0900–1000	30	28.2	7.3	30.9	30.9	6.1	33.1	28.9	32.3	−2.1	3.5	26
1000–1100	30	34.6	7.6	37.5	37.4	4.7	39.4	35.3	38.8	−2.8	8.5	22
1100–1200	30	38.2	8.1	41.2	41.1	5.2	43.7	37.2	42.7	−2.8	9.2	21
1200–1300	30	39.5	6.2	41.6	41.3	17.4	44.8	39.3	43.5	−2.2	5.1	16
1300–1400	30	36.3	7.7	39.0	38.8	8.7	43.1	32.5	41.3	−2.1	4.8	21
1400–1500	30	31.3	6.9	34.7	33.0	8.6	39.1	26.7	36.1	−1.5	2.6	22
1500–1600	30	24.4	6.9	26.6	26.2	4.1	30.4	24.1	28.6	−2.0	3.5	28
1600–1700	30	16.1	5.9	19.3	20.0	1.4	21.5	13.6	20.1	−1.4	0.8	36
1700–1800	30	9.2	3.2	11.0	10.9	2.0	12.4	8.2	11.3	−1.3	0.3	34
1800–1900	30	3.7	1.1	4.1	4.0	0.8	4.9	2.9	4.4	−1.2	0.9	29
1900–2000	30	0.4	0.2	0.4	0.4	0.0	0.6	0.3	0.5	−0.8	−0.1	42

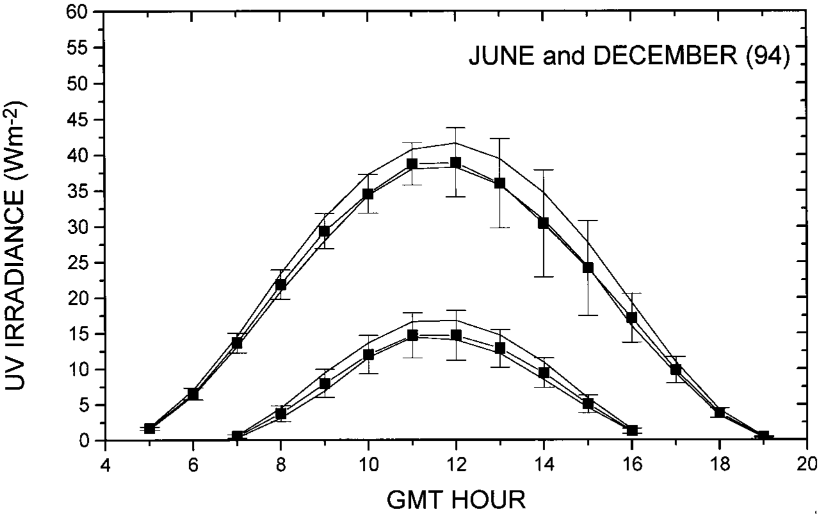

Figure 7. Hourly monthly average of the UV irradiance (W/m^2) for June and December in 1994. Average values together with superior and inferior quartiles

From this statistical analysis, it can be observed that the median values are slightly higher than the average and the modal values, which suggests that the distribution of the UV global irradiance is not a normal distribution. The negative skewness values reveal an asymmetrical distribution (negative). The arithmetic mean is commonly used as an average value for normal distributions which, as stated above, seems not to be the case. Therefore, the use of other parameters such as the median and the inferior and superior quartiles is considered.

As the differences between the inferior quartiles and the minimum values are high mainly in the central hours of the day, it can be concluded that the minimum values are not representative of the UV global irradiance in Granada. On the other hand, the differences between the superior quartiles and the maximum values are low, the higher difference not exceeding 1.9 W/m^2, thus indicating greater representation of maximum values. These results agree quite well with those of Martinez-Lozano *et al.* (1996).

The S.D. are not very high but increase in the central hours of the day when the UV global irradiance is higher. This variability can be studied with the CV parameter (%). The month of June represents high stability with low values for CV, fluctuating between 8% in the central hours and 28% early in the afternoon (Table II, 1994). The same comments apply to the results for 1995.

Figure 7 shows the UV radiation for the two months that show the most different behaviour, that is, June and December in 1994. The average values and the inferior and superior quartile are presented and the bars correspond to the S.D. In this figure it can be seen that the inferior quartile is close to the average value and the S.D. are higher in the central hours, symmetrically distributed in December but not in June. This could be explained by a major presence of clouds in the afternoon hours in summer months that lead to a high variability. Considering the whole year, the variation coefficient in 1994 is higher in April and May and lower in June and July, showing a high variability during such months.

4. CONCLUSIONS

Ultraviolet radiation was measured by means of an Eppley TUVR, since the end of 1993. The analysis of 2 years of UV radiation (295–385 nm) and broadband global radiation data in the southeast of Spain show the following results:

(i) The maximum values for UV irradiance take place in summer months and the minimum values in winter months, presenting a symmetrical pattern around solar noon every month. The seasonal variations come as a consequence of the longer path of radiation with greater solar zenith angles;
(ii) the study of the ratio of UV to broadband global radiation reveals that the maximum values are coincident with a higher frequency of cloudiness. The behaviour of this ratio suggests that the presence of cloudiness markedly affects this ratio. This is a consequence of the greater transmittance of clouds in the UV waveband in comparison with longer wavelengths. In this sense, cloudy conditions lead to higher values of this ratio (reaching an increase ranging from 3 to 5%). This variability of the ratio UV to broadband global solar irradiance due to clouds effects must be taken into account when the UV (UVA + UVB) is estimated from broadband global measurements;
(iii) the slant path of beam radiation through the atmosphere influences this ratio; a longer path, i.e. lower solar elevation angles, leads to lower values of this ratio. In any case, cloudy conditions have a greater influence than optical air mass. In fact, under cloudless situations the behaviour of the ratio UV to broadband global irradiance is controlled by optical air mass, but under cloudy conditions this parameter is of secondary order;
(iv) a statistical analysis of the UV irradiance data shows a distribution that is not normal. The great variability of the spring period, which corresponds more to changing weather, is in high contrast with the notable stability during the summer months. The study of the distribution evidences that the maximum values are illustrative of the UV global irradiance in Granada, but the minimum values are not representative. These results agree quite well with those from Martinez-Lozano *et al.* (1996);
(v) the results of this study for 1994 and 1995 show similar behaviour and statistics as those reported by Martinez-Lozano *et al.* (1994, 1996) for another locality in Spain, using similar equipment;
(vi) these results suggest that the estimation of UV global irradiance from broadband solar global irradiance must be done considering the variability of the above-mentioned ratio. This could be achieved by the modelling of the ratio UV to broadband global irradiance in terms of optical air mass and cloudiness.

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