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Near ultraviolet radiation at the earth's surface: measurements and model comparisons

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ABSTRACT

A 3-year record of simultaneous measurements of daily ultraviolet (≃0.290–0.380 μm) and total global solar (≃0.290–2.9μm) irradiations at Corvallis, Oregon, USA (44°34′N, 123°14′W; 65.5 m) has been analyzed to determine whether any systematic relationship exists between the two. Regression of the ultraviolet (UV) radiation on the total global (G) solar radiation yields coefficients of determination in excess of 0.980; the mean value of 0.054 (s.d.: 0.008) for the ratio UV/G that we obtain is within the range of values reported by other investigators based on measurements of different record lengths and averaged over different time periods. Comparison of the measured, clear-day noon irradiances with computed values in vertically inhomogeneous turbid atmospheric models with ozone, aerosols and surface albedo as variable parameters, shows agreement between experiment and theory to within ±10%.

1. Introduction

The near ultraviolet (≃0.300–0.400 μm) solar radiation received at the earth's surface plays an important rôle in biological, environmental, ecological and photochemical processes occurring at or near the ground. Thus, a clear understanding of the availability, and of the spatial and temporal variations of this radiation is an integral part of investigations in areas such as the diurnal history of the formation and dissipation of photochemical smog (Nader, 1969; Shettle, 1972), the incidence of skin diseases (e.g., immediate pigment darkening, polymorphous light eruption) in humans on exposure to sunlight (Brodthagen, 1969; Smith, 1972), the photodecomposition of commonly-used herbicides (e.g., Devrinol, Picloram and Atrazine), and photodegradation of plastics, paints, dyes and natural and synthetic fibers. Preliminary studies have also indicated some association between exposure to broad-band ultraviolet solar radiation and the incidence of cataracts in the human eye (Zigman, 1977). The life histories of marine organisms are affected by the magnitude of the ultraviolet irradiations they are subjected to (Jokiel, 1980; Worrest, 1982) in the course of the day. Climatological estimates of the broad-band ultraviolet irradiation are also used in the design of protectants for microbial agents used to control forest insects (M. J. Stelzer, 1983, personal communication).

The major modifiers of the ultraviolet radiation reaching the earth's surface are atmospheric ozone, turbidity, clouds and surface reflectivity. Considerable effort has been expended on modelling the climatology of ultraviolet radiation (e.g., Dave and Furukawa, 1966; Halpern et al. 1974; Sundararaman et al., 1975); however, observational data are very meager. Generally, experimental work is directed towards developing simple regression models for the estimation of the ultraviolet irradiation in terms of the more commonly measured total global solar irradiation whenever data on simultaneous measurements of the two are available. It is against this background that we wish to report on the results of an insolation monitoring

program that has been underway at Corvallis, Oregon, USA (44°34'N, 123°14'W; 65.5 m) since 1980.

2. Experimental program

We use an Eppley Model TUVR radiometer to measure the broad-band global ultraviolet radiation (≃0.290–0.380 μm) incident on a horizontal surface. The instrument utilizes a hermetically sealed selenium barrier-layer photocell protected by a quartz window as the detector; the spectral interval of interest is isolated with an encapsulated interference filter. A specially designed quartz diffuser disc placed in front of the filter-detector assembly ensures close (±2%) adherence to the Lambert cosine law of response for solar zenith angles up to 80°; the instrument is linear to within ±2% and it is calibrated under natural conditions of exposure by comparison with an Eppley standard ultraviolet pyranometer incorporating a non-wavelength selective thermopile sensor. Greater details of design, construction and operation of the UV radiometer are found in Coulson (1975).

The total global solar radiation (≃0.290–2.9 μm) is measured with an Eppley precision spectral pyranometer which satisfies the majority of requirements set for a Class 1 radiation sensor by the World Meteorological Organization (WMO, 1971). It is periodically calibrated on the 1975 Absolute Radiation Scale against regional standards maintained at the Solar Radiation Facility, US National Oceanographic and Atmospheric Administration, Boulder, Colorado, USA.

Irradiances, in units of W m^{-2}, are measured 6 times/min and the 1-min, hourly and daily irradiations, in units of kJ m^{-2}, are subsequently computed and stored on magnetic tape by a Hewlett-Packard Model 9825 computer. A conservative estimate of the accuracy of the irradiations thus measured is ±2%. The observing site affords optimum exposure to the global radiation sensor, with practically no obstructions extending beyond 3° above the plane of the sensor element, especially from east-north-east, through south, to west-north-west, so that the vertical component of diffuse sky radiation lost by obstruction amounts to much less than 1% of the total (WMO, 1971).

3. Results and discussion

3.1. *Daily ultraviolet irradiations*

Our measurements over the 3-year (1980–82) period indicate that the *monthly mean daily* ultraviolet irradiation varies by nearly a factor of 7 in the course of the year from 171 kJ m^{-2} in December to 1191 kJ m^{-2} in July. This annual range of variation in the received ultraviolet radiation is somewhat less than but comparable to what has been reported by Baker-Blocker (1980) for different sites (latitude range: ≃43° N to 45° N) in New York, USA. The *yearly mean daily* ultraviolet irradiation is found to be 649 kJ m^{-2}.

As mentioned earlier, it has generally been the practice (Schulze and Grafe, 1969; Kvifte et al., 1983) to express the ultraviolet (UV) irradiation as a fraction of the total global (G) solar irradiation at the surface when simultaneous measurements of both are available, to determine whether any systematic relationship exists between the two as is suggested by the data shown in Fig. 1. Accordingly we have shown in Table 1 the means, standard deviations and sample sizes of the ratio (UV/G) for 3 cases, namely, when all the available data for the 3-year period are considered to constitute a single sample, when the same are grouped according to season (fall: October, November and December; winter: January, February and March; spring: April, May and June; summer: July, August and September) and when they are grouped according to sky conditions. In the last case, instead of using surface observations of cloud amount, we have utilized the relatively less subjective fractional sunshine FS, the ratio of the hours of bright sunshine measured with a Campbell-Stokes sunshine recorder (threshold: ≃4.2 kJ m^{-2} min^{-1}) to the length of the day from sunrise to sunset, as an indicator of sky conditions.

It is apparent from the entries in Table 1 that the ratio UV/G exhibits considerable dispersion; seasonal dependence, if any, is not very obvious even though the mean value of the ratio is at a minimum during summer. However, an examination of the dependence of this ratio on sky conditions indicates a relative enhancement on days with FS < 0.15 (cloud amount >6 oktas) compared to the values prevailing on days with FS > 0.85 (cloud amount <2 oktas) even though both the daily ultraviolet and total global solar irradiations decrease with increasing cloudiness. This

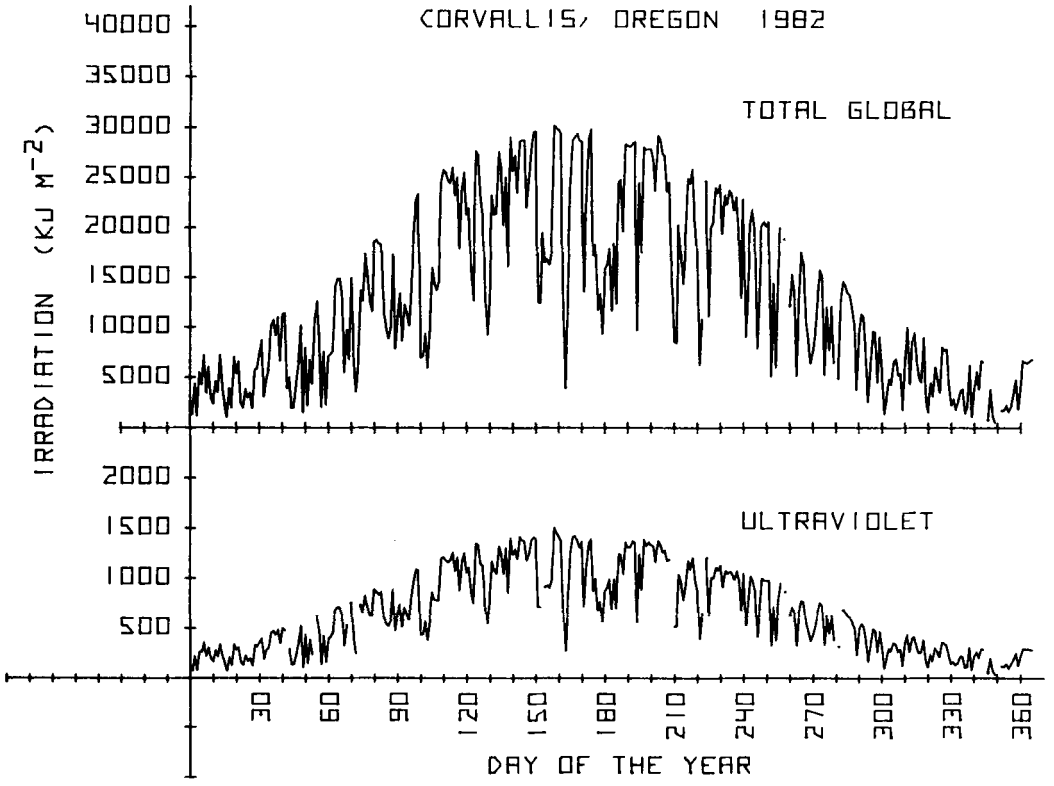

Fig. 1. The variation of the daily total global solar and broadband ultraviolet irradiations at Corvallis, Oregon, USA during 1982.

Table 1. *The daily broad-band ultraviolet (0.290–0.380 μm) irradiation expressed as a fraction of the total global solar (~0.290–2.9 μm) irradiation at Corvallis, Oregon, USA*

	Seasonal dependence					Dependence on sky conditions		
Parameter	all data	fall	winter	spring	summer	FS < 0.15	0.15 ≤ FS ≤ 0.85	FS > 0.85
m	0.054	0.056	0.057	0.053	0.050	0.063	0.051	0.046
σ	0.008	0.009	0.008	0.005	0.005	0.006	0.004	0.002
n	1002	259	245	255	243	289	544	169

m: mean value. *σ*: standard deviation. *n*: number of observations. FS = fractional sunshine.

tendency for a relative enhancement of the UV component of the total global solar radiation under cloudy skies is also seen in the computational work of Halpern et al. (1974) and of Spinhirne and Green (1978). Furthermore, we obtain results which correspond very closely with what we have discussed so far when data for any of the 3 years are analyzed separately; this may be considered indicative of the stability of performance of the radiation sensors over long periods of continuous operation.

It is instructive to compare our results with those obtained by other investigators. Kvifte et al. (1983), using the *monthly mean* values of the ultraviolet and total irradiations at various sub-arctic locations (latitude range: 55° N to 75° N) in the Nordic countries, find the ratio UV/G to vary from 0.044 to 0.056. Schulze and Grafe (1969),

from their analysis of radiation measurements at Hamburg (53°33′N, 9°59′E), find that the *monthly mean daily* ultraviolet irradiation over the spectral interval 0.315–0.400 μm is about 5–6% of the total global irradiation. Observations of the ultraviolet irradiation at Amundsen-Scott station, Antarctica, during the austral summer of 1979–80 indicate that, under clear skies, the hourly average value of the UV component is about 4–5% of the total irradiation (Baker-Blocker et al., 1982). Collins (1973) has reported the UV (0.290–0.385 μm) irradiation to be 6–8% of the total global at Aspendale, Australia.

Simple linear regression of UV on G, utilizing all the available data over the 3-year (1980–82) period, yields the relationship UV (kJ m^{-2}) = 52.3 (kJ m^{-2}) + 0.047 G (kJ m^{-2}), with a coefficient of determination, R^2, in excess of 0.98. If we exclude cloudy days (FS < 0.15; cloud amount ⩾6 oktas) on which G was less than 4000 kJ m^{-2} from the regression, we find that the intercept changes to 64.1 kJ m^{-2} while R^2 and the slope remain relatively unaffected. Stewart (1980), considering clear day, 1-min irradiations over a 3-day period, finds that the slope of the regression line varies from 0.043 to 0.047 at Albany, NY, USA (42°40′N, 73°50′W).

3.2. *Comparison with model computations*

We shall examine in this section the degree of correspondence that exists between our clear-day measurements and computed values of broad-band UV irradiances in cloud-free models of a plane parallel turbid atmosphere. The irradiances measured at noon on days on which there was no evidence of cloud or other local pollutants within 1 h of noon will be used for this purpose. We shall discuss in some detail the computational results for a 9-layer, vertically inhomogeneous atmosphere, using the total amount of ozone in the atmospheric column, atmospheric turbidity and surface albedo as variable parameters. The results for a homogeneous atmosphere obtained using a simple procedure suggested by Bird (1982) will also be included in this comparison with measurements.

Each of the 9 layers in the inhomogeneous model contains different fractions of the purely scattering gaseous (non-ozone) component, ozone and aerosols (Table 2). We assume that the aerosols are non-absorbing, spherical water particulates with a refractive index of 1.340 (Hale and Querry, 1973)

Table 2. *Vertical distribution of the various atmospheric constituents in the 9-layer inhomogeneous model atmosphere*

Layer boundaries (km)	% of constituent in layer			
	Molecular (non-ozone)	Ozone	Aerosols	
			clear	hazy
0–1	11.3	1.0	45.5	60.2
1–2	10.2	0.9	19.9	22.0
2–4	17.6	1.5	12.4	11.0
4–6	14.2	1.3	4.1	1.6
6–9	16.2	2.1	4.0	1.2
9–13	14.0	5.9	4.9	1.4
13–19	10.0	19.1	6.1	1.7
19–25	3.9	32.5	2.3	0.7
25–50	2.5	35.7	0.8	0.2

over the spectral region 0.290–0.380 μm. The relationship between the aerosol number density $n(r)$ and particle radius r is given by (McClatchey et al., 1970):

$$\frac{n(r)}{\Delta r} = C \cdot r^{-4} \text{ for } 0.1\,\mu\text{m} < r < 10\,\mu\text{m},$$

$$\frac{n(r)}{\Delta r} = C \cdot 10^{4} \text{ for } 0.02\,\mu\text{m} < r < 0.1\,\mu\text{m},$$

$$\frac{n(r)}{\Delta r} = 0 \text{ for } r < 0.02\,\mu\text{m and } r > 10\,\mu\text{m}.$$

C is a normalization constant. The model atmosphere rests on a Lambert surface; thus, the reflected radiation is isotropic and unpolarized independently of the angle of incidence and polarization of the incoming radiation.

We use the adding method (Takashima et al., 1972) to compute the spectral irradiances at the surface at 19 wavelengths, 0.005 μm apart, over the spectral interval 0.290–0.380 μm for 3 different states of atmospheric turbidity. We use the normal aerosol attenuation optical thickness at λ = 0.55 μm, τ_A (0.55 μm), to label these 3 different model atmospheres; thus, when τ_A (0.55 μm) = 0, the atmosphere is purely molecular. When τ_A (0.55 μm) = 0.172, the atmosphere is "clear" with 4.44 × 10^8 aerosol particles in a 1 cm^2 atmospheric column above the ground, with the near-surface aerosol number density so adjusted as to yield

approximately 25 km ground visibility. Similarly, when τ_A (0.55 μm) = 0.599, the atmosphere is "hazy" with 1.57 × 10^9 aerosol particles in the atmospheric column, with the near-surface aerosol number density so adjusted as to yield approximately 5 km ground visibility. We have listed the wavelengths at which the irradiances have been computed, the extraterrestrial spectra used (Thekaekara, 1974; C. Fröhlich, 1981, personal communication to Solar Energy Research Institute, Golden, Colorado, USA) and the ozone absorption coefficients (Vigroux, 1953) in Table 3; we have used ozone absorption coefficients corresponding to a temperature of −44 °C, since most of the ozone is located above an altitude of 13 km (Table 2).

We have shown in Table 4 the computed values of the broad-band (0.290–0.380 μm) UV irradiances in the 3 variants of the inhomogeneous atmosphere referred to above. We have considered both a non-reflecting (A = 0) surface and a surface with a Lambert albedo of 0.25. The total amount of ozone has been taken as 0.340 atm · cm, a typical mid-year value for midlatitude locations such as Corvallis (Dutsch, 1971). We see that the Fröhlich spectrum yields integrated UV irradiances which are, on the average, less than those obtained with the Thekaekara spectrum; the disparity is of the order of 10% over the entire range of solar zenith angles.

The transition of the model atmosphere from "molecular" to "clear" results in decreases of up to 5% in the irradiances as the solar zenith angle, θ_0, changes from 6.3° to 77.6°; the decreases are larger (5–15%) when the transition is from

Table 3. *Atmospheric model parameters*

Wavelength (μm)	Extraterrestrial direct normal solar irradiance (W m^{-2} μm^{-1})* Fröhlich (1981)	Thekaekara (1974)	Ozone absorption coefficient (atm · cm)$^{-1}$
0.290	466.3	482.0	35.5 × 10^0
0.295	558.6	584.0	19.1
0.300	535.9	514.0	9.30
0.305	558.3	603.0	4.42
0.310	622.0	689.0	2.40
0.315	692.7	764.0	1.09
0.320	715.1	830.0	7.80 × 10^{-1}
0.325	832.9	975.0	4.10
0.330	961.9	1059.0	1.05
0.335	931.9	1081.0	8.00 × 10^{-2}
0.340	900.6	1074.0	5.57
0.345	911.3	1069.0	1.70
0.350	975.5	1093.0	7.14 × 10^{-3}
0.355	975.7	1083.0	2.37
0.360	975.9	1068.0	1.76
0.365	992.9	1132.0	6.00 × 10^{-4}
0.370	1119.9	1181.0	0
0.375	1111.9	1157.0	0
0.380	1103.8	1120.0	0

* Linear interpolation has been used when necessary.

Table 4. *Variation of broad-band ultraviolet irradiance (W m^{-2}) with atmospheric turbidity in the inhomogeneous model atmosphere with 0.340 atm · cm of ozone*

	θ_0(degrees)											
	6.3		14.4		22.5		30.4		60.0		77.6	
τ_A(0.55 μm)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
(i) Surface albedo = 0												
0	51.8	46.5	50.1	45.0	47.0	42.3	42.9	38.5	20.1	18.1	5.9	5.3
0.172	51.4	46.1	49.6	44.6	46.5	41.8	42.3	38.0	19.4	17.5	5.6	5.0
0.559	49.4	44.3	47.6	42.7	44.5	39.9	40.2	36.1	17.5	15.8	5.0	4.5
(ii) Surface albedo = 0.25												
0	56.2	50.5	54.3	48.8	51.0	45.8	46.5	41.7	21.7	19.6	6.3	5.7
0.172	56.0	50.3	54.1	48.6	50.8	45.6	46.2	41.5	21.2	19.0	6.1	5.5
0.599	54.3	48.8	52.3	47.0	48.9	43.9	44.2	39.7	19.3	17.3	5.5	4.9

(a) Irradiances computed using the extraterrestrial solar spectrum of Thekaekara (1974).
(b) Irradiances computed using the extraterrestrial solar spectrum of Fröhlich (1981, personal communication).

"molecular" to "hazy" over the same range of solar zenith angles. This dependency on atmospheric turbidity appears to be independent of the total amount of ozone. Similarly, changing the surface albedo A from 0 to 0.25 results in the enhancement of the broad-band UV irradiance by 8–10% relative to the prevailing values with a non-reflecting ground.

The dependence of the integrated UV irradiance on the total amount of ozone is less pronounced; thus, our computations indicate decreases of 2–4% as the total amount of ozone changes from 0.280 atm · cm to 0.380 atm · cm. This is understandable since absorption by ozone in the Hartley (0.250–0.320 μm) and Huggins (0.310–0.360 μm) bands is effective at wavelengths lying below 0.350 μm and the irradiances at these wavelengths contribute less than half (~47%) of the total broad-band irradiance.

As mentioned earlier, we have also computed the broad-band UV irradiance in a homogeneous model of a cloud-free turbid atmosphere using the simple procedure developed by Bird (1982). It is assumed in this model that the irradiance at the surface is independent of the vertical distributions of the gaseous and aerosol components of the atmosphere and is determined by the total amounts of these constituents in the vertical column (Dave and Halpern 1976; Shettle and Green, 1974). We have assumed the size distribution of the weakly absorbing aerosols (refractive index: 1.53–0.006i) to be given by the bimodal, rural aerosol model described by Shettle and Fenn (1975). Comparison of the spectral irradiances obtained using this model with the results of more rigorous radiative transfer computations in multi-layered atmospheric models has shown agreement to within ±5% for low and intermediate values of the solar zenith angle (Bird, 1982).

There were 63 clear days, mostly in spring and summer, during the 3-year (1980–82) period on which no clouds or other local pollutants could be detected within 1 h of noon. We have shown in Fig. 2 the ultraviolet irradiances measured at noon on these days along with the computed values in the homogeneous and inhomogeneous model atmospheres. We have assumed the total amount of ozone to be 0.340 atm · cm and the Lambert surface albedo to be 0.25 in both models. The normal aerosol attenuation optical thickness at the wavelength of 0.55 μm, τ_A(0.55 μm), was 0.172 in the inhomogeneous model and 0.240 in the homogeneous model.

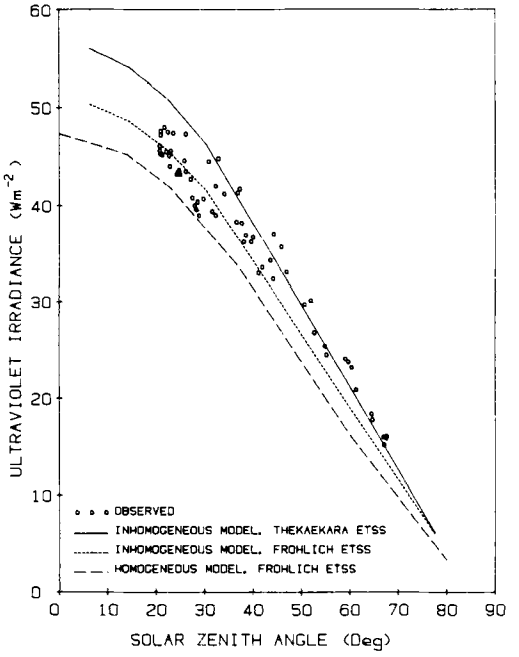

Fig. 2. Comparison between measured and computed values of clear-day noon ultraviolet irradiances (ETSS: extraterrestrial solar spectrum).

There is reasonable agreement between the measured and computed noon UV irradiances. We notice that the measured irradiances, while tending to be close to the relatively larger values computed using the Thekaekara extraterrestrial solar spectrum in the inhomogeneous model atmosphere during fall and winter (solar zenith angle >45°), cluster around the computations performed with the Fröhlich spectrum during spring and summer (solar zenith angle <45°). Such behavior and the scatter in the measurements are mainly due to the seasonal and short-term, weather-related departures of the prevalent atmospheric and surface parameters, namely, the nature and extent of atmospheric turbidity (as determined by the size distribution, refractive index and the total number of aerosols in the atmospheric column), total amount of ozone and surface albedo from what we have used in the model computations. Thus, the relatively low turbidity of the predominantly maritime polar air masses in residence at our location during late fall

and winter (Decker, 1960) would allow more of the ultraviolet radiation to reach the surface; on the other hand, the high levels of turbidity associated with the continental subtropical air masses in residence during late spring and summer would decrease the received ultraviolet radiation. Similarly, even though the seasonal variation in the total amount of ozone (from ~0.290 atm · cm in November to ~0.370 atm · cm in April) would only account for small departures of the measured irradiances from the values computed with 0.340 atm · cm of ozone, the rapid fluctuations in the ozone amount from day-to-day which could exceed the seasonal variation at midlatitude locations, especially during winter and spring (Dutsch, 1971) could affect the UV irradiances in an appreciable manner. The possible variation in the surface albedo in the ultraviolet at and around the site of measurements are expected to be within the range of values (0–0.25) used in the model computations.

The lower irradiance values in the homogeneous model are primarily due to the larger attenuation by the aerosols which exhibit small but finite absorption in the ultraviolet; similar lowering of the ultraviolet radiation reaching the earth's surface when absorbing aerosols are present in the atmosphere has also been noticed by Halpern et al. (1974) in their computations of sea level solar radiation in the biologically active spectrum.

Using these clear-day, noon irradiances, we find that the transmissivity of the cloud-free atmosphere over Corvallis for broad-band ultraviolet radiation ranges from 0.54 (December) to 0.67 (June) in the course of the year if we use the Fröhlich extraterrestrial solar spectrum; these values would be 0.49 and 0.61, respectively, if the Thekaekara spectrum is used.

4. Summary and conclusions

Our analysis of a 3-year (1980–82) record of simultaneous measurements of the daily broad-band ultraviolet (0.290–0.380 μm) and total global solar (0.290–2.9 μm) irradiations at Corvallis, Oregon, USA has shown that the two are highly correlated; simple regression of the ultraviolet on the total solar irradiation yields values for the coefficient of determination in excess of 0.98. The ratio borne by the ultraviolet to the global irradiation has a mean value of 0.054, with a standard deviation of 0.008. No seasonal dependence of this ratio could be detected; however, there is some indication of a slight dependence on cloud amount.

Comparison between measured clear-day, noon ultraviolet irradiances and the computed values in cloud-free models of a turbid atmosphere indicates reasonable correspondence between the two, to within $\pm 10\%$. The model computations also show that the broad-band ultraviolet irradiance is relatively more sensitive to changes in atmospheric turbidity and surface albedo than to changes in the total amount of ozone in the atmospheric column.

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