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SPECTRAL BAND RESOLUTION OF SOLAR RADIATION IN ATHENS, GREECE

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ABSTRACT

A 14-year (1977–1990) record of global solar radiation measurements performed in Athens, Greece, has been utilized to determine the distribution of radiant energy in the various wavelength bands. The monthly mean values of the irradiation ratios in the spectral intervals, blue (0·380–0·525 μm), green–orange (0·525–0·630 μm), red (0·630–0·710 μm), and photosynthetically active radiation (PAR) (0·380–0·710 μm) and the global irradiation (0·3–2·8 μm) compare favourably with values reported in the literature for different locations over a wide geographical area.

The irradiation ratios exhibit seasonal variations attributable to changes in local air-mass climatology. It is observed that the proportion of the radiant energy in the various spectral bands relative to the global solar irradiation increases as sky conditions change from 'clear' to 'partly cloudy'. Finally, the observed seasonal dependence of the broad-band spectral energy distribution is essentially caused by changes in the composition of the air masses (turbidity, airborne pollutants, clouds) in residence at the measurement site in the course of the year.

KEY WORDS Irradiation ratio Band energies Photosynthetically active radiation turbidity

1. INTRODUCTION

The increase in terrestrial applications of solar energy has given impetus to the study of solar energy availability in many areas of the world. With the increasing use of spectrally selective devices, such as photovoltaic cells for electrical generation and selective absorbers for thermal collectors, and for practical applications in environmental and agrometeorological research, current interest is not only in the total amount of solar energy reaching the Earth's surface, but also in its spectral composition.

The global irradiance, measured as the sum of direct solar radiation and the diffuse sky radiation on a horizontal surface, depends on a large number of factors: astronomical, geographical, physical, and meteorological. At the Earth's surface, the distribution of solar energy between wavelength regions depends on the solar zenith angle, the atmospheric turbidity (aerosol content, composition, and size distribution), the atmospheric content of absorbing gases (ozone, water vapour, and carbon dioxide), cloudiness, and surface albedo.

Several computations have been made of the spectral distribution of the direct and scattered solar components for various atmospheric models and surface conditions (Robinson, 1966; Shettle and Green, 1974; Kneizys *et al.*, 1980; Kvifte *et al.*, 1983; Rao, 1984). The effects of clouds are often neglected owing to the extreme complexity and variability of clouds varying from high thin cirrus clouds to thick cumulus clouds and low stratus clouds, all of which have different influences on the spectral composition of radiation. Direct measurements are rather scarce (Klein and Goldberg, 1976; Mani *et al.*, 1977; Bird *et al.*, 1982; Rao, 1984), and there is obviously a need for more data on this subject.

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It is well known that one of the most important factors that affect the amount of solar irradiation reaching the Earth's surface is the existence of aerosol particles in the atmosphere. Airborne particulate and gaseous pollutants alter the solar energy incident at the ground in two ways: by depleting the total energy and by changing the relative amounts of direct and diffuse radiation. Natural or man-made aerosols have different effects both on the intensity and on the spectral distribution of solar irradiance. This may have important consequences for processes that depend on light quality, such as plant development and photosynthesis (Unsworth and McCartney, 1973).

In view of the general absence of high-resolution spectral measurements, which are possible only with very sophisticated instruments (Bird *et al.*, 1982), it has been the usual practice to obtain estimates of the irradiation in the various spectral regions in terms of the more commonly measured total (0.3–2.8 μm) global solar irradiation (Kvifte *et al.*, 1983; Rao, 1984). Such estimates, which are in the form of irradiation ratios in the various spectral intervals and the total global irradiation, are initially derived from simultaneous measurements of broad-band spectral and total global radiation. Subsequently they are used to estimate the spectral energy distribution of received solar radiation at locations for which only the total global irradiation data exist.

In this study, the spectral-band resolution of solar irradiation is studied. The measurements of direct solar radiation, with and without filters, and of global irradiation for the whole spectrum were made in Greece at the National Observatory of Athens (NOA). The correlation between the direct irradiation in several spectral bands and the global all-wavelength solar irradiation is examined. In addition, the dependence of direct irradiance in the various wavelength bands on other parameters is considered.

2. DATA UTILIZED

For the study of the spectral-band resolution of solar energy in Athens, global solar radiation and pyrheliometric data for the period 1977–1990 were used. The observations were performed at 0820, 1120, 1420, and 1720 hours local standard time (LST is 2 h ahead of UT) whenever clouds were not present in the sightpath. In the present study only measurements at 1120 and 1420 hours are considered, since measurements from 0820 and 1720 hours, are rather scarce. The instruments used were Linke–Feussner type pyrheliometers equipped with Schott filters OG530, RG630 (formerly RG2), RG695 (formerly RG8), and a quartz filter, measuring radiation above cut-off wavelengths of, respectively, 0·525 μm, 0·630 μm, 0·710 μm, and 0·380 μm. For the quartz filter, especially, the cut-off wavelength is approximately 0·250 μm (Iqbal, 1983). However, in the case of the present study this cut-off is 0·380 μm as given by Athens Observatory (Kampetzides, pers. comm., 1992). Subtracting readings made with different pyrheliometer filters made it posible to evaluate the incident energy in the wavelength bands 0·380–0·525 μm (blue), 0·525–0·630 μm (green–orange), 0·630–0·710 μm (red), and 0·380–0·710 μm. The latter band corresponds to the so-called photosynthetically active radiation (PAR band) (Monteith, 1973; Stamper and Allen, 1979; Rao, 1984; Karalis, 1989). An Eppley precision spectral pyranometer (PSP) was used for measuring total global irradiance (0·3–2·8 μm).

The instruments were situated at the National Observatory of Athens on a small hill 110 m above mean sea-level (about 30 m above the street level of Athens) in the centre of Athens, a city known for high pollution. The instruments were compared once a year with a 'standard' set. Differences in the calibration of the different instruments were thereby kept within an uncertainty of less than 2 per cent. The absolute calibration of the 'standard' set was controlled by comparison with an Angstrom pyrheliometer. Taking into account temperature effects, linearity of response, and the 'cosine effect', as given by the manufacturer in the certificates to the instruments, the error in absolute readings of global radiation is believed to be not more than 5 per cent for solar zenith distances less than *ca.* 80°. For zenith distances greater than 80°, the cosine effect introduces greater uncertainty. In the band energies the errors may also be somewhat larger (*ca.* 8 per cent), since these energies are obtained as differences between readings of four filter pyrheliometers.

The measurements were corrected for the attenuation of the light by filters according to the instructions of the Radiation Commission (CSAGI, 1957) and those of the manufacturer. In addition the measured irradiances were corrected for variation in temperature of the thermopiles. It is conservatively estimated that the error introduced by these factors is less than 0·5 per cent (Karalis, 1974).

Since the pyrheliometric measurements depend on weather and sky conditions, the number of observations is smaller in winter months and greater in summer months. The cloudiness at the times of the pyrheliometric observations varied between zero and 3 oktas and occasionally 4 or 5 oktas. In the following, the characteristics of the various spectral bands and related quantities are considered on a monthly basis.

3. RESULTS AND DISCUSSION

Rao (1984) and Karalis (1989) found from measurements and computations that under cloud-free conditions the irradiances in the visible band are sensitive to atmospheric turbidity. In the present study, to account for the effects of airborne pollutants and aerosols on the direct beam of solar radiation, the whole period of the observations 1977–1990, was subdivided into two data sets, the first one covering the period 1977–1983 and the second one the period 1984–1990. According to Karras *et al.* (1990), air pollution episodes occurred more frequently during the second period (1984–1990). During the first period air pollution levels are insignificant, while photosmog episodes are rather scarce. The results for these two periods are presented separately.

It has been the practice generally to express the measured, monthly broad-band spectral irradiation as a fraction of the total global solar irradiation in order to detect any correlation between the two (Kvifte *et al.*, 1983; Rao, 1984). In Table I, monthly mean values of the irradiation ratios between the designated spectral intervals and the total are summarized (hereafter referred to as spectral irradiation ratios), based on a 7-year (1977–1983) record of measurements. The mean values (m), the standard deviations (SD), the coefficients of variation (CV $=$ SD/m), and the sample sizes (n), of the spectral irradiation ratios are shown in Table II. Two cases are given: in one all the available data over the 7-year period are considered to constitute a single sample; and in the other the data are grouped by season (winter, December–February; spring, March–May; summer, June–August; Autumn, September–November).

The entries in Table I indicate that the monthly mean broad-band spectral irradiations vary approximately in the same manner as the total global irradiation in the course of the year. However, the variation from month to month of the various spectral irradiation ratios points to the dependence of the spectral energy distribution of the received solar radiation on short-term and seasonal changes in the atmospheric and surface parameters. This dependence becomes very apparent when the seasonal values of the spectral irradiation ratios listed in Table II are examined. In the red spectral band (0·630–0·710 μm) the mean spectral irradiation is nearly constant, with a relatively weak maximum value during the summer (June–July) and a minimum value during the spring period.

Table I. Monthly mean values of the irradiations in designated spectral intervals expressed as fractions of the total global solar irradiation (0·3–2·8 μm), for the first data set, 1977–1983

	Spectral irradiation ratios (μm)			
Month	0·380–0·525	0·525–0·630	0·630–0·710	0·380–0·710
January	0·188	0·143	0·091	0·423
February	0·208	0·159	0·089	0·456
March	0·201	0·152	0·089	0·442
April	0·203	0·147	0·089	0·439
May	0·205	0·151	0·091	0·447
June	0·220	0·159	0·093	0·472
July	0·218	0·161	0·092	0·471
August	0·212	0·157	0·091	0·460
September	0·213	0·160	0·091	0·465
October	0·208	0·156	0·092	0·456
November	0·195	0·153	0·089	0·437
December	0·188	0·155	0·091	0·434

Table II. Monthly global irradiations in designated spectral intervals expressed as fractions of the total (0·3–2·8 μm) global solar irradiation, for the first data set, 1977–1983. Values of turbidity parameters β_0 and α_0 are included

Spectral interval (μm)		All data	Autumn	Winter	Spring	Summer
0·380–0·525	m	0·218	0·216	0·204	0·213	0·224
	SD	0·061	0·059	0·060	0·062	0·061
	CV	0·279	0·272	0·295	0·291	0·272
	R	0·092				
	n	1280	326	130	237	587
0·525–0·630	m	0·163	0·165	0·160	0·157	0·166
	SD	0·044	0·043	0·041	0·041	0·047
	CV	0·271	0·261	0·259	0·263	0·280
	R	0·055				
	n	1280	326	130	237	587
0·630–0·710	m	0·092	0·092	0·091	0·090	0·093
	SD	0·017	0·015	0·021	0·012	0·018
	CV	0·183	0·168	0·231	0·138	0·194
	R	0·033				
	n	1280	326	130	237	587
0·380–0·710	m	0·473	0·473	0·455	0·459	0·483
	SD	0·038	0·058	0·042	0·036	0·034
	CV	0·080	0·122	0·092	0·078	0·070
	R	0·059				
	n	1280	326	130	237	587
β_0			0.20	0.16	0·26	0·25
α_0			0·92	1·18	0·63	0·72

In the blue spectral band the annual variation is greater than in the red band, with maxima during summer (June) and minima during winter (December and January). In the green–orange band the respective variation is weakly lower than in the blue one, with maxima during the summer period (July) and minima during the winter (January). These results are in accordance with the fact that during the winter months diffuse radiation contributes relatively more to the global radiation because of the low sun. This leads to a displacement of the spectral distribution towards shorter wavelengths. A similar trend shows the PAR band with a maximum in summer (June) and minimum in winter (January).

In Table II the ratio R $(=(m_{MAX}-m_{MIN})/m)$ is defined as the difference between the maximum and minimum seasonal values (m) of the spectral irradiation ratio in any given spectral interval to its average value. Using this ratio, which can be viewed as a measure of the seasonal variation (Rao, 1984), it is found that the spectral irradiation ratio in the blue region exhibits the largest variation ($R=0·092$), followed by the ratios in the bands, PAR ($R=0·059$), green–orange ($R=0·055$), and red ($R=0·033$), in that order (see Table II).

The dependence of the various spectral irradiation ratios on sky conditions is shown in Table III. Using surface observations of cloud amount (CL), the data were grouped into two categories: for 'clear' sky, $CL \leq 2$ oktas, and for 'partly cloudy' sky $CL > 2$ oktas. It is apparent that all the spectral irradiation ratios are increased as the sky conditions change from 'clear' to 'partly cloudy'. This relative enhancement of the visible component of the total global irradiation under 'partly' cloudy conditions has also been noticed by other investigators (Kvifte *et al.*, 1983; Rodskjer, 1983; Rao, 1984). This is due to the fact that clouds attenuate the incoming solar radiation at infra-red wavelengths greater than 0·7 μm, both by absorption and scattering, whereas attenuation by clouds in the visible spectrum is due to scattering alone (De Vault and Katsaros, 1983).

Table III. Dependence of the ratios between the various spectral irradiations and the total global solar irradiation on sky conditions, for the first data set, 1977–1983

Spectral interval (μm)		'Clear' sky (CL$\leqslant$2 oktas)	'Partly cloudy' sky (CL >2 oktas)
0·380–0·525	*m*	0·199	0·223
	SD	0·060	0·055
	CV	0·300	0·245
	n	734	546
0·525–0·630	*m*	0·143	0·182
	SD	0·044	0·032
	CV	0·310	0·174
	n	734	546
0·630–0·710	*m*	0·089	0·092
	SD	0·011	0·019
	CV	0·125	0·205
	n	734	546
0·380–0·710	*m*	0·431	0·497
	SD	0·096	0·065
	CV	0·224	0·131
	n	734	546

In Tables IV–VI the results obtained using the data set of 1984–1990 are summarized in the same form as before. The seasonal variation for the various spectral intervals shows similar trends to the first data set. Thus, the blue region exhibits the largest seasonal variation ($R=0{\cdot}059$), followed by the ratios in the bands PAR ($R=0{\cdot}043$), green–orange ($R=0{\cdot}035$), and red ($R=0{\cdot}033$). However, the seasonal variation is not so large as in the first data set, e.g. compare values of R between the two data sets.

A comparison of the various spectral irradiation ratios shows an increase in the second data set, except for the red band. This spectral band shows lower values than in the first period, while in the green–orange band the values are slightly greater. In the blue and PAR bands an enhancement is observed. These variations are due to the different atmospheric conditions and could be explained by changes in atmospheric turbidity and/or aerosols size and composition. Thus, values of turbidity parameters, Angstrom's coefficient β_0 and wavelength exponent α_0, for both data sets are included in Tables II and V, respectively. As the turbidity is

Table IV. As in Table I, but for the second data set, 1984–1990

	Spectral irradiation ratios (μm)			
Month	0·380–0·525	0·525–0·630	0·630–0·710	0·380–0·710
January	0·228	0·162	0·088	0·478
February	0·231	0·165	0·087	0·483
March	0·243	0·168	0·088	0·498
April	0·256	0·166	0·088	0·509
May	0·262	0·168	0·090	0·520
June	0·256	0·173	0·091	0·520
July	0·260	0·174	0·092	0·523
August	0·266	0·168	0·092	0·524
September	0·261	0·169	0·090	0·520
October	0·249	0·168	0·089	0·505
November	0·245	0·164	0·090	0·500
December	0·223	0·164	0·091	0·479

Table V. As in Table II, but for the second data set, 1984V–1990

Spectral interval (μm)		All data	Autumn	Winter	Spring	Summer
0·380–0·525	*m*	0·254	0·254	0·246	0·255	0·261
	SD	0·041	0·040	0·038	0·040	0·038
	CV	0·160	0·159	0·155	0·158	0·146
	R	0·059				
	n	1395	366	185	249	595
0·525–0·630	*m*	0·168	0·168	0·166	0·168	0·172
	SD	0·024	0·024	0·019	0·020	0·027
	CV	0·143	0·142	0·114	0·121	0·159
	R	0·035				
	n	1395	366	185	249	595
0·630–0·710	*m*	0·091	0·090	0·089	0·089	0·091
	SD	0·021	0·022	0·018	0·021	0·020
	CV	0·228	0·235	0·204	0·239	0·225
	R	0·033				
	n	1395	366	185	249	595
0·380–0·710	*m*	0·513	0·512	0·501	0·512	0.524
	SD	0·039	0·038	0·032	0·038	0·036
	CV	0·076	0·074	0·064	0·073	0·069
	R	0·043				
	n	1395	366	185	249	595
β_0			0.38	0.21	0·52	0·55
α_0			0·73	1·09	0·31	0·22

Table VI. As in Table III, but for the second data set, 1984–1990

Spectral interval (μm)		'Clear' sky (CL ≤ 2 oktas)	'Partly cloudy' sky (CL > 2 oktas)
0·380–0·525	*m*	0·253	0·255
	SD	0·037	0·043
	CV	0·146	0·169
	n	715	682
0·525–0·630	*m*	0·167	0·175
	SD	0·023	0·026
	CV	0·137	0·149
	n	715	682
0·630–0·710	*m*	0·087	0·092
	SD	0·016	0·024
	CV	0·183	0·253
	n	715	682
0·380–0·710	*m*	0·507	0·522
	SD	0·032	0·044
	CV	0·063	0·084
	n	715	682

increased, an enhancement of the blue and green–orange spectral bands is observed, while the red waveband remains nearly constant. It is clear that atmospheric turbidity increased considerably during the second data set (1984–1990). Mean monthly values of α_0 are much less than unity during the spring and summer periods. These values are generally higher during the winter period suggesting the predominance of smaller particles during winter. This arises first from the washout and rainout of large and giant aerosols, the washout being most effective for the giant particles, and second from a change in the weather synoptic air mass. However, the values are still lower than that of the first period. At this point one must keep in mind that measurements usually were obtained during strong insolation. From this point of view the levels of gaseous pollutants considerably increased, so that photosmog episodes were likely observed.

Furthermore, the small values of α_0 means that large particles are more numerous. It must be noted that α_0 attains in many individual cases (during spring and summer months) negative values. This fact reveals that very large particles are present in the atmosphere. This is supported by the fact that air pollution episodes occurred more frequently during this period than during the first period 1977–1983 (Karras *et al.*, 1990).

Additionally, from the intercomparison between the two data sets, it is clear that the irradiation ratio in the red spectral band is lower in the second period. On the other hand, in the blue band the values are greater, while the green–orange values are relatively constant. Aerosols and airborne pollutants decrease the direct solar beam, which will be largely compensated by an increase in the diffuse flux (Peterson and Flowers, 1977). This leads to a displacement of the spectral distribution towards shorter wavelengths (Kvifte *et al.*, 1983). The above is consistent with the view that when a shift in spectral distribution takes place, the energy taken away from the 'middle band' to one side of the spectrum is approximately compensated by energy from the other side (Robinson, 1966).

It is instructive to examine how the spectral irradiation ratios that were determined compare with the results of other investigators. Thus, comparative verification results, reported by several investigators together with those obtained in the present analysis, are summarized in Table VII. One notes from the table that the results reported by other authors, although the locations of interest have the characteristics of a rural site, are comparable to the results obtained in the present analysis, mainly for the first data set. It is clear from the turbidity values that atmospheric conditions during the first period tend to be more representative of a rural city than an urban one (Karalis, 1989). It must be noted here that values of turbidity, β_0, and wavelength exponent, α_0, for the first data set are close to that reported by Karalis (1976) for an earlier period, when air pollution problems in Athens city were not presented.

Karalis (1989) presented the characteristics of the PAR band in Athens for an earlier period, 1962–1976, and he reported a mean value of the PAR ratio of the order of 0·450, which is less than the corresponding PAR values in both data sets of the present study. At this point it may be thought that the two data sets used here are the physical continuation of Karalis' data set. Therefore, taking this into account it appears that the value of the PAR band ratio has increased over time: 0·450 for the period 1962–1976, 0·473 for the period

Table VII. Comparative verification results of the present study and those reported in the literature

Reference	Blue (0·380–0·525 μm)	Green–orange (0·525–0·630 μm)	Red (0·630–0·710 μm)	PAR (0·380–0·710 μm)	Location
Goldberg and Klein (1977)	–	–	–	0·450	Jerusalem Rockville Barrow
Blackburn and Proctor (1983)	–	–	–	0·470 0·450 0·540	Guelph, Canada
Kvifte *et al.* (1983)	0·207 0·179	0·215 0·200	0·146 0·094	0·460 0·480	Nordic countries
Rodskjer (1983)	–	–	0·080	0·457 0·473	Ultuna, Sweden
Rao (1984)	0·222	0·149	0·086	0·457	Corvallis, Oregon
Present (1977–1983) analysis (1984–1990)	0·218 0·254	0·163 0·168	0·092 0·091	0·473 0·513	Athens Greece

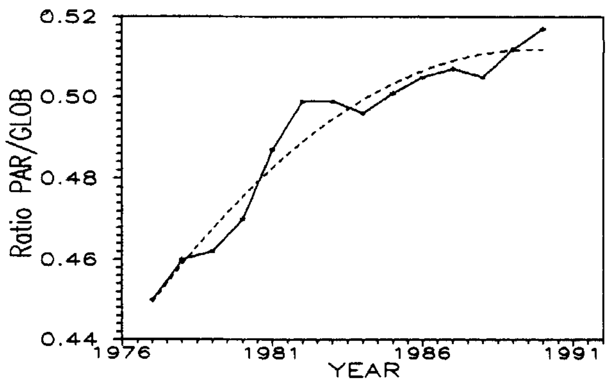

Figure 1. Time sequence of the mean values of the ratio PAR/GLOB for the period 1977–1990. A second degree polynomial curve has been fitted (dashed line)

1977–1983, and 0·513 for the last period, 1984–1990. This led to a more careful examination of the mean monthly values of PAR for each year and for both data sets. The time sequence of the mean values of PAR is given in Figure 1. It becomes very clear that from the beginning of the examined period a continuous enhancement of the PAR ratio occurs. The increasing values of the PAR ratio can be explained by changes in atmospheric turbidity and/or aerosol type. Large or giant aerosols, as mentioned above (see values of α_0), occur in the atmosphere and these scatter the radiation more intensively in the forward direction. A consequence of this process is the increasing ratio of diffuse to global solar radiation (Chacko *et al.*, 1972). In this way a displacement of the spectral distribution towards shorter wavelengths is observed. Thus, the upward trend of the PAR band relative to global solar irradiance occurs.

4. CONCLUDING REMARKS

The nature and extent of presently available experimental data are such that meaningful comparisons can be drawn between the present measurements and those reported by other investigators, especially in the PAR band, with additional comparisons for other bands in the cases of the experimental data sets of Kvifte *et al.* (1983) and Rao (1984). The comparisons reveal that the mean values of 0·473 and 0·513 that were obtained for the monthly spectral irradiation ratio in this interval, for the two data sets respectively, are fairly representative.

It is observed that the proportion of the radiant energy in the spectral intervals, 0·380–0·525 μm, 0·525–0·630 μm, 0·630–0·710 μm, and 0·380–0·710 μm, relative to the total (0·3–2·8 μm) global solar irradiation increases as sky conditions change from 'clear' to 'partly cloudy'. This is attributable mainly to changes in the relative importance of the processes of absorption and scattering by clouds in the attenuation of the incoming solar radiation in different regions of the spectrum. The observed seasonal dependence of the broad-band spectral energy distribution of the received solar radiation is essentially caused by changes in the composition of the air masses (turbidity, precipitable water, and clouds) in residence at the measurement site in the course of the year.

The intercomparison between the two data sets reveals that the observed differences between the irradiation ratios in the various spectral bands are caused essentially by atmospheric turbidity, a meteorological factor that is affected by air pollutants in the Athens basin, a city renowned for its increasingly high pollution levels during the last decade.

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