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Spatial distribution and yearly evolution of the solar radiation in Spain

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SYNOPSIS
The finite Fourier series has been fitted to the measured values of the monthly long-term mean irradiation from 41 stations in Spain. The original data has been interpolated to 17 localities and the value of the average irradiation, amplitude and phase angle of the first harmonic are given for 58 localities altogether; 7 of them outside the Iberian peninsula. A set of maps show the distribution of the irradiation in MJ/m^2 day on a horizontal surface for yearly and seasonal periods.

INTRODUCTION

The analysis of the spatial distribution of the solar radiation and its change along the year helps to gain a better understanding of the synoptic climatological features and to infer correlations between irradiation and other meteorological parameters. This is also needed to evaluate the solar energy resource.

Some papers have been published on solar radiation data in Spain [1, 2, 3] containing maps of the seasonal and yearly spans of the insolation levels for the Iberian peninsula. In a former paper [4] we have applied the harmonic analysis to monthly solar radiation data collected along the year for a total of 41 Spanish localities. The results show the amplitude of the first harmonic accounts for a very large portion of the variance. The plotting on maps of the variance and phase of the first and second harmonics reveals how the climatological features affect the radiation levels and give a more accurate view of the insolation distribution and weather influence. Prior to this study two papers have made use of this method with one [5] and 24 [6] Spanish meteorological stations.

The Fourier analysis provides a method of fitting a periodic function to a set of values given at certain intervals. This procedure makes the analysis of some statistics such as the mean and the variance relatively easy [7]. In the present work, for each locality, the evolution of the solar radiation along the year has been described by two parameters: the amplitude and phase angle.

RADIATION DATA

The measured radiation data were provided by the Instuto Nacional de Meteorologia on a daily base. To be used in the analysis the data were converted in monthly values. The meteorological stations are placed in 41 localities, 34 of them are in the Iberian peninsula, between 36.5°N latitude in Cadiz and 43.47°N in Santander; three in the Canary Islands, between 27.93°N in Las Palmas and 28.95°N in Lanzarote; two localities in the Balearic isles, and one in Ceuta (35.92°N) and another in Melilla (35.28°N) in north Africa. The number of available years ranges from three only in Tortosa (40.82°N) to thirteen years in Oviedo (43.35°N).

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FINITE FOURIER SERIES

The monthly mean value of the solar radiation intensity, H_r may be expanded [7] in terms of periodic function as:

$$H(t) = R_o + 2\sum_{n=1}^{n-1} R_m \operatorname{Cos}(2\pi\frac{mt}{N} + \phi_m)$$
$$R_n \operatorname{Cos}(2\pi\frac{nt}{N}) \quad (1)$$

Where,

$$R_m = (A_m + B_m)^{1/2} \quad (2)$$

$$\phi_m = \arctan(-\frac{A_m}{B_m}) \quad (3)$$

and

$$A_m = R_m \operatorname{Cos}\phi_m \quad (4)$$

$$B_m = -R_m \operatorname{Sin}\phi_m \quad (5)$$

Where R_m is the amplitude and ϕ_m is the phase angle of the mth harmonic. The constants A_m and B_m are determined making use of the othogonality relations of the sine and cosine functions, as it follows:

$$A_m = \frac{1}{N}\sum_{r=-n}^{n-1} H_r \operatorname{Cos}(2\pi\frac{mr}{N}) \quad (6)$$

$$B_m = \frac{1}{N}\sum_{r=-n}^{n-1} H_r \operatorname{Sin}(2\pi\frac{mr}{N}) \quad (7)$$

for $m = 0, 1, \ldots, n$. A_0 is the mean of the set of N values of H_r, being $N = 2n$.

The expression obtained taking only the first harmonic describes the annual change of the solar radiation in each chosen locality. That shows a maximum and a minimum value spaced six months apart from each other. The second harmonic, for $m = 2$, represents the semiannual tendency in the data, it shows two maxima and two minima equally spaced. The terms of the higher order describe oscillations of shorter period.

RESULTS AND DISCUSSIONS

The monthly mean values have been obtained using the available daily measured data for 41 stations and they have been used in the fitting for the calculation of A_m and B_m coefficients. From the expressions (2) and (3) the amplitudes R_m and phases ϕ_m have been computed. The results obtained for all the localities give an excellent fitting until the fifth decimal figure in MJ/m^2day units.

For each site studied the variance has been computed and the results are given in another paper [4] along with the results of the first harmonic contribution to the total variance. In the Iberian peninsula the results obtained, in percentage of the total variance, for this parameter, related to the chosen stations range from 96.7 in Oviedo (43.35° N) to 99.6 in Valencia (39.48° N).

In the present work the values of the mean, the amplitude and phase angle of the first harmonic have been given in Table 1, where the original data and the interpolated results for 17 stations have been included. Comparing with the output for the 21 localities referred in [6] the values of the mean here given are slightly lower than the ones we obtained while the results of the other parameters are very close. To compare the results of phase angle it must be borne in mind that in reference [6] daily values were used.

In order to have a more relevant information and make a comparative analysis we have plotted the rsults on a series of maps of the Iberian peninsula in a rectangular projection. Figure 1 shows the isolines of the annual mean values of the solar radiation out of the atmosphere in MJ/m^2 day for the 41 localities, with 1367 W/m^{-2} as the solar constant value [8]. As was expected, there is a trend to follow the lines of the same latitude and there is a gradient increase from north to south in about 0.4 MJ/m^2 day for each degree latitude. That uniform distribution of the isolines without atmosphere when compared with the irregular distribution of the isolines in the presence of atmosphere may help us to understand how the local climate affects the absorption and scattering of radiation.

To show the evolution of the solar radiation along the year over the Iberian peninsula, the mean values of the irradiation intensity in MJ/m^2day have been plotted in a seasonal span. Figure 2 shows the average values for the period over the months of December, January and February. The isolines record places of the same average irradiation for that period. For the greater part of the surface the trend to follow the geographic parallels resembling the distribution of the isolines of Figure 1 for radiation outside the atmosphere can be observed. There is an uniform gradient increasing as we move southward, as has been pointed out by Font [3]. The smallest record 4.8 MJ/m^2 day is obtained in Santiago (42.88° N) and the greatest, 11 MJ/m^2 day in Almeria (36.85° N).

The distribution of the mean value of the irradiation intensity for March, April and May, has been depicted in Figure 3. Comparing the isolines with the ones of Figure 2 (first quarter) it can be observed they have been deflected southward in the west and northward at the east. Around three localities Madrid, Saragossa and Albacete there is a gradient, with the greatest value in those places.

In Figure 4 the mean value of the irradiation over the three months June, July and August is shown. The shape of the isolines can be seen resembling the ones of the former period but more stressed. The gradient around Saragossa happens to be greater, changing from 19.52 MJ/m^2 day in Pamplona to 27.64 MJ/m^2 day at Saragossa, a variation of 8 MJ/m^2 day in 60 km.

The map of the isolines for the mean of the radiation for Autumn (September, October and November) is depicted in Figure 5. A clear trend is observed to recover the regular shape as the winter period (Figure 2) approaches with an increasing gradient southward and smoother local gradient around Saragossa and Albacete. In Figure 6 the

Table 1 **Annual average, Amplitude and phase of the first harmonic for the locations under study. (The stations with interpolated results are marked with *).**

	Locality	Longitude	Latitude	Annual average	Amplitude	Phase angle
	Albacete	−1.85	38.93	18.11	9.90	6.35
	Alicante	−0.50	38.36	18.04	9.28	6.31
	Almeria	−2.38	36.85	18.51	8.58	6.26
*	Avila	−4.70	40.65	15.81	9.35	6.41
	Badajoz	−6.81	38.88	16.69	9.70	6.34
	Barcelona	2.15	41.41	14.04	7.88	6.35
	Bilbao	−2.93	43.30	10.73	6.51	6.43
	Burgos	−3.63	42.36	14.82	9.46	6.42
*	Caceres	−5.70	39.80	16.22	9.24	6.39
	Cadiz	−6.30	36.51	18.11	8.63	6.34
	Castellon	−0.02	39.95	15.80	8.56	6.27
	Ciudad Real	−3.91	38.98	16.46	8.95	6.39
	Cordobā	−4.80	37.85	16.70	8.98	6.38
*	Cuenca	−2.07	40.07	16.49	9.32	6.38
*	Gerona	2.83	41.98	14.52	8.22	6.33
*	Gijon	−5.65	43.50	11.29	6.35	6.26
	Granada	−3.78	37.18	17.34	8.78	6.40
*	Guadalajara	−1.88	40.85	15.82	9.13	6.40
*	Guipuzcoa	−2.03	43.30	13.42	8.40	6.40
	Huelva	−6.95	37.26	18.51	9.51	6.26
*	Jaen	−3.78	37.77	17.26	8.94	6.37
*	La Coruña	−8.40	43.37	12.72	8.38	6.40
	Lanzarote	−13.6	28.95	16.84	5.60	6.13
	La Palma	−17.7	28.62	17.25	5.20	6.13
*	La Rioja	−2.22	41.33	15.64	9.25	6.42
	Las Palmas	−15.4	28.15	18.67	6.78	6.35
	Leon	−5.65	42.58	14.28	8.63	6.42
	Lerida	0.63	41.61	13.97	8.35	6.26
	Logroño	−2.40	42.63	15.00	9.76	6.35
	Lugo	−7.48	43.25	14.14	9.00	6.37
	Madrid	−3.71	40.45	17.10	10.58	6.41
	Malaga	−4.48	36.66	17.06	9.03	6.27
	Melilla	−2.95	35.28	17.92	8.26	6.17
	Menorca	4.23	39.87	15.65	8.64	6.29
	Molina	−1.88	40.85	15.69	8.92	6.41
	Murcia	−1.11	37.98	16.86	9.09	6.28
*	Orense	−7.85	42.33	13.04	8.38	6.43
	Oviedo	−5.86	43.35	10.96	6.06	6.24
*	Palencia	−4.53	42.01	14.19	8.68	6.39
	Palma de M	2.65	39.57	15.33	8.90	6.31
	Pamplona	−1.65	42.76	12.54	7.78	6.43
	Salamanca	−5.50	40.95	15.28	9.04	6.39
	Santander	−3.81	43.46	11.40	7.21	6.36
	Santiago	−8.41	42.88	12.24	8.32	6.38
*	Segovia	−4.12	40.95	15.99	9.69	6.41
	Sevilla	−5.90	37.41	17.64	9.55	6.34
	Soria	−2.51	41.60	15.74	9.30	6.45
	Tarragon	0.87	40.95	15.63	8.86	6.27
*	Teruel	−1.10	40.35	16.07	9.08	6.34
	Toledo	−4.33	39.55	15.61	8.87	6.45
	Tortosa	0.50	40.81	15.10	8.53	6.33
	Valencia	−0.38	39.48	15.45	8.05	6.29
*	Valladolid	−4.72	41.65	14.61	8.85	6.40
	Vigo	−8.63	42.23	12.59	8.12	6.57
*	Vizcaya	−2.93	43.30	10.78	6.54	6.43
*	Zamora	−5.75	41.50	15.15	8.98	6.39
	Zaragoza	−1.01	41.66	17.61	11.34	6.40

annual average of the radiation intensity in MJ/m^2 is shown. It can be observed that the isolines show a pattern more similar to the ones of the second and third periods.

CONCLUSIONS

In a global assessment of the output shown in the maps of Figure 1 extraterrestrial radiation and Figure 2 to 5 of the measured radiation on the

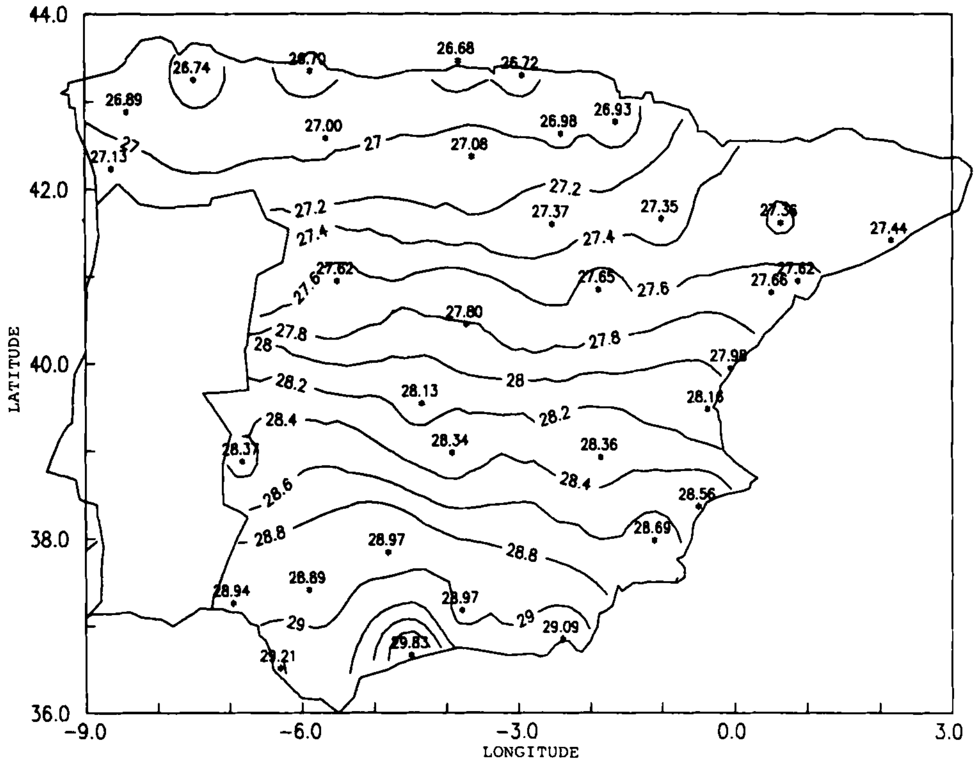

Figure 1
Map of the extraterrestrial annual average radiation.

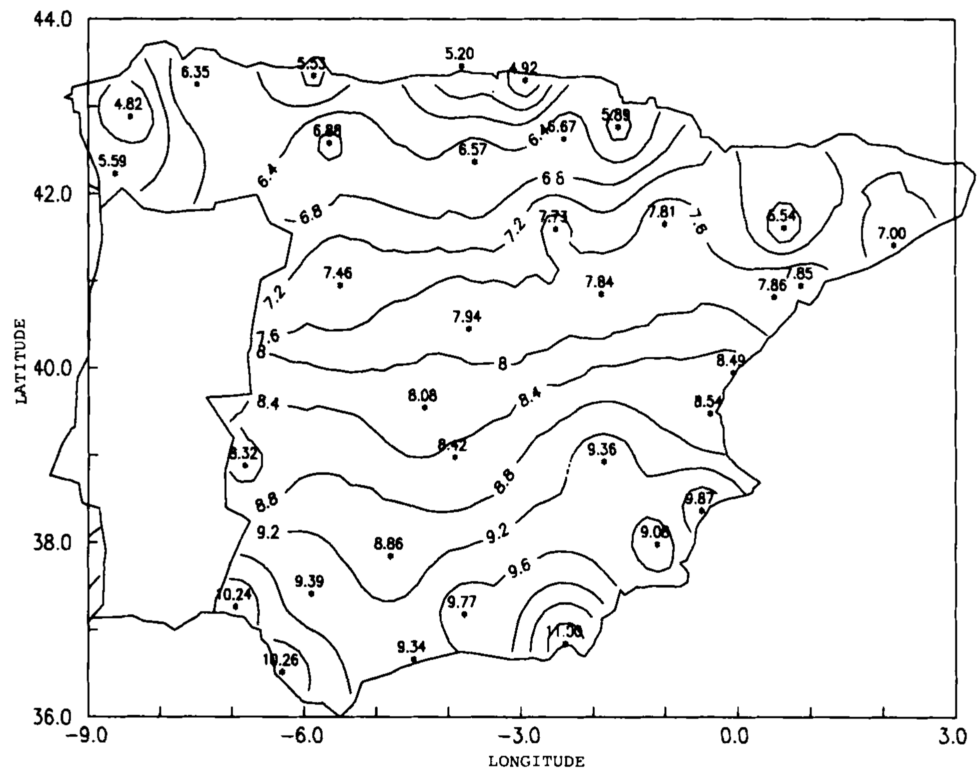

Figure 2
Average radiation over the first quarterly period in MJ/m^2.day.

surface, it can be pointed out that the effect of the atmosphere over the Iberian peninsula acts as a non uniform filter to the radiation, being less homogeneous during the second and third seasonal period (Spring and Summer) that the first and fourth (Winter and Autumn) where the isolines reflect in a more defined way the local climate of some specific regions. In the second and third period, local gradients are produced in the centre, north-east and south-east of the peninsula.

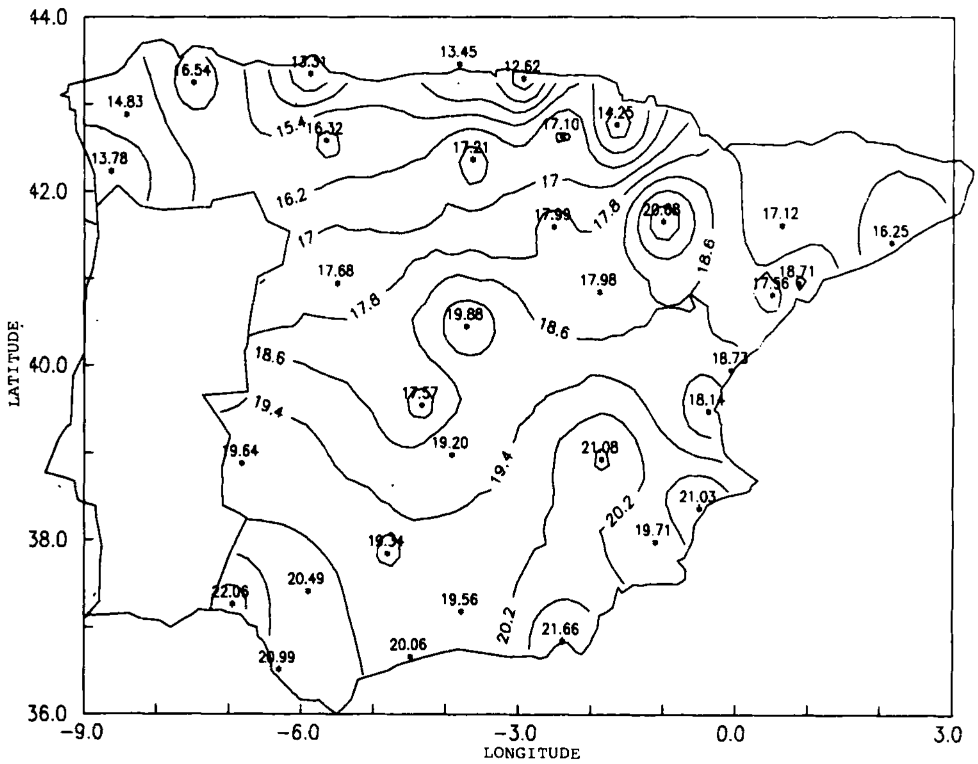

Figure 3
Average radiation over the second quarterly period in MJ/m^2.day.

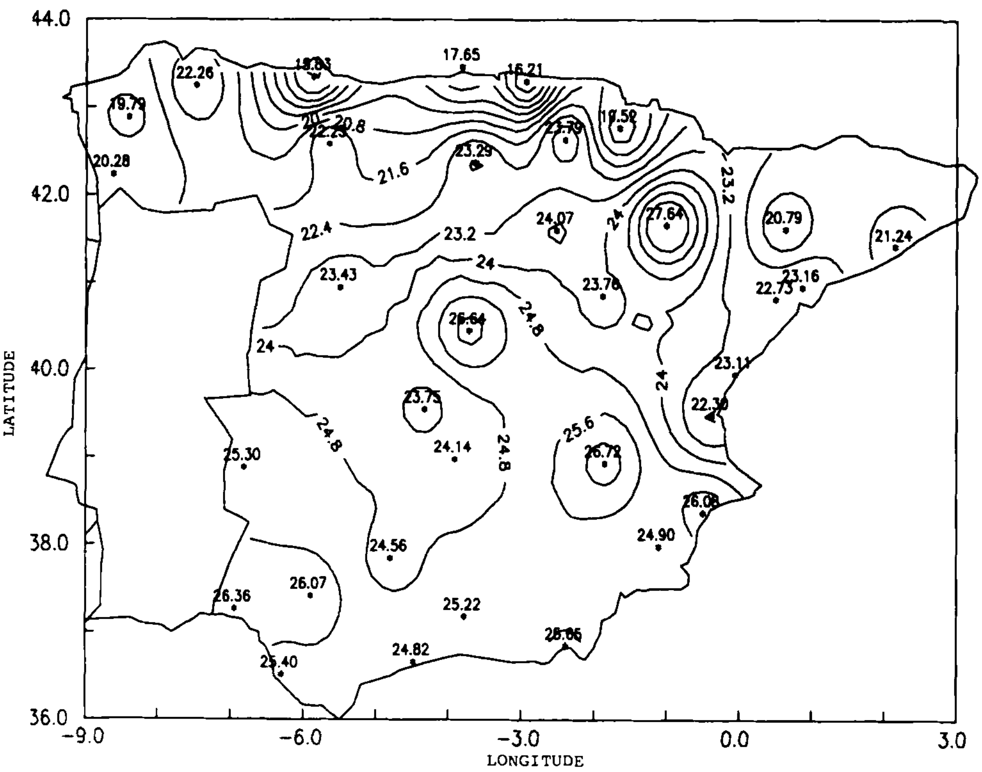

Figure 4
Average radiation over the third quarterly period in MJ/m^2.day.

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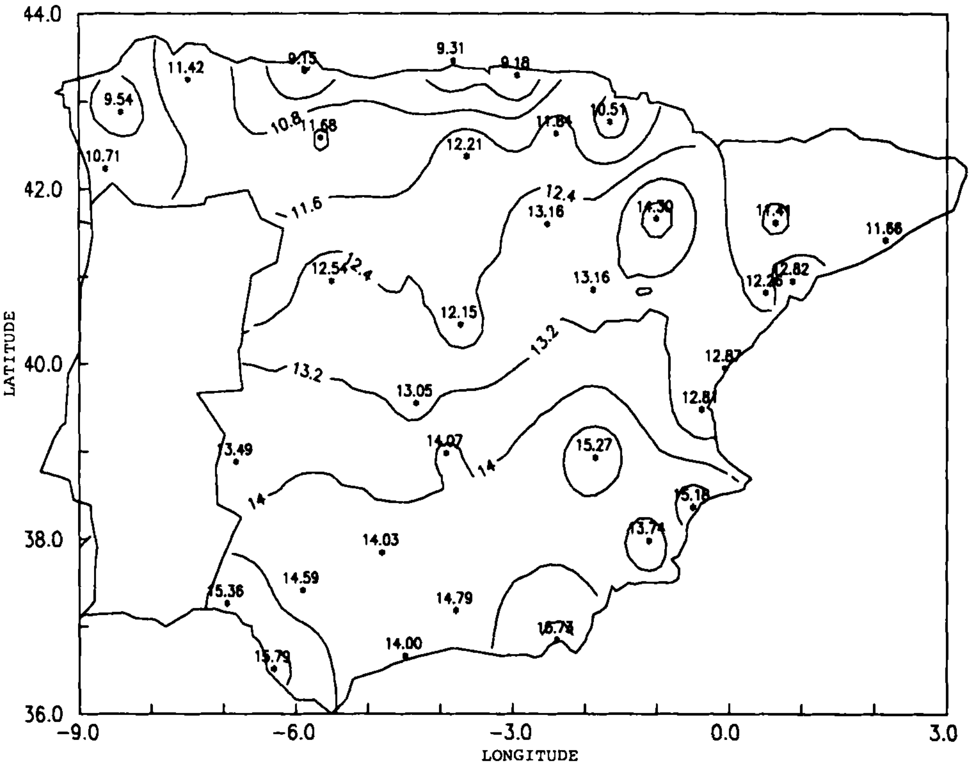

Figure 5
Average radiation over the fourth quarterly period in MJ/m^2.day.

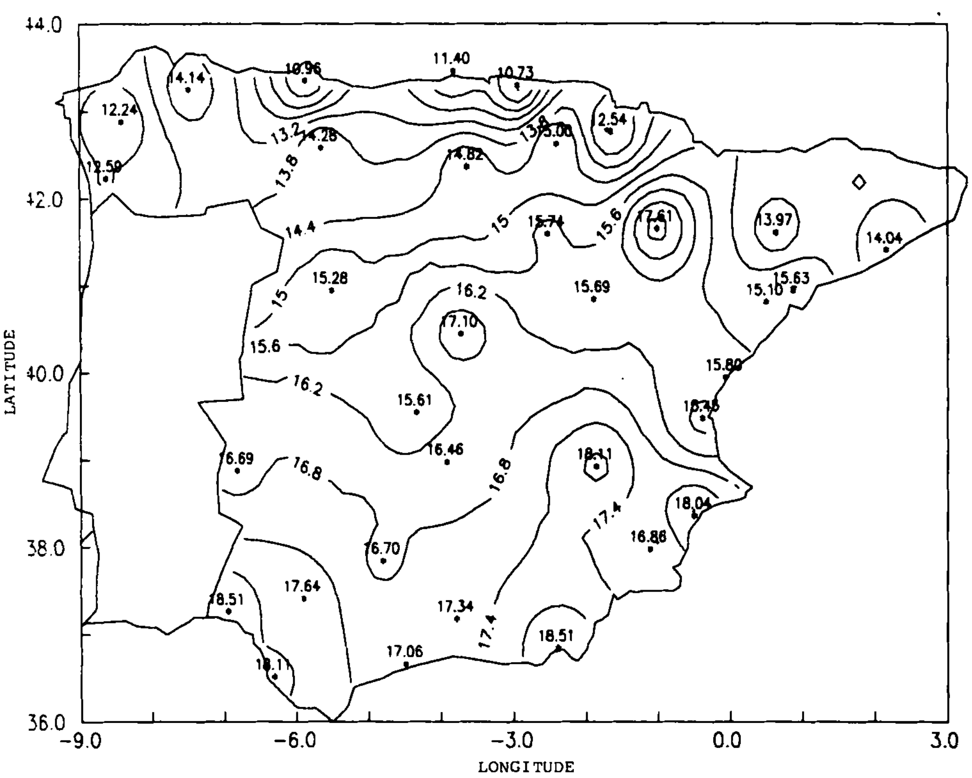

Figure 6
Annual average of the radiation measured on the surface in in MJ/m^2.day.

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