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Satellite derived solar irradiance over Mexico

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RESUMEN

A partir de datos del satélite GOES y utilizando el modelo estadístico de Tarpley (1979), se determinan valores de irradiancia solar global para México. Se forma una base de datos de 7 imágenes digitales diarias obtenidas de julio 1982 a diciembre 1984. Los promedios mensuales y estacionales, con resolución de 1° × 1° latitud-longitud se presentan en un mapa fisiográfico de México. Se obtienen también superficies tridimensionales que muestran la distribución latitudinal y longitudinal de la irradiación solar global. El error estándar de la estimación, con respecto a datos piranométricos de superficie es de 3 a 5%.

Los resultados muestran claramente dos regímenes del flujo de irradiación solar sobre México: De octubre a abril, se observan isopletas muy regulares en los mapas mensuales mientras que las superficies latitudinal y longitudinal se distribuyen uniformemente en la mayor parte del país mostrando una casi ausente modulación de la radiación por nubes indicando la llamada "estación seca". Los valores máximos se sitúan en abril, salvo en el norte del país en donde se localizan durante junio y julio. De mayo a septiembre se presenta el segundo régimen de irradiación solar global que coincide con la estación lluviosa y de frecuente nubosidad; las isopletas se distorsionan presentando encurvamientos y nodos, particularmente sobre las sierras. Los valores mínimos de radiación se localizan durante septiembre. Estos resultados muestran claramente la fuerte modulación del campo de radiación por las nubes y la absorción del vapor de agua. Como consecuencia de lo anterior, se observa un gradiente latitudinal de irradiación solar global tal que $\partial E/\partial\phi \geq 0$ ocurre durante la estación seca, mientras que $\partial E/\partial\phi \leq 0$ se presenta durante la estación lluviosa. Estos hechos indican transporte de energía hacia los polos durante la primavera y el verano mediante una fina combinación de parámetros astronómicos y geográficos, es decir, en el norte del país, una mayor duración de la insolación y ausencia de nubes, determinan una mayor incidencia de radiación solar, mientras en el sur, una fuerte modulación del flujo de radiación a través de la presencia constante de nubes reduce la energía solar entrante.

Finalmente, se muestra que la distribución geográfica del flujo de radiación solar depende fuertemente del relieve.

ABSTRACT

Global solar irradiance is determined for Mexico from GOES satellite data using, the statistical method of Tarpley (1979). Seven daily digital images taken from GOES satellite over Mexico for the period July 1982 - December 1984 are analysed. Monthly and seasonal means are evaluated by computing monthly averages of the daily totals at a 1° × 1° latitude-longitude grid points. Values of the monthly average daily totals are plotted on a physiographic map of Mexico. Tridimensional surfaces of the distribution of global solar irradiance on Mexico are obtained as a function of latitude and longitude. The standard error of the estimates with respect to ground-truth data is between 3 to 5%.

The results show clearly the existence of two-well defined patterns of solar irradiance over Mexico from October to April the isopleths are very regular on the monthly maps whereas the latitudinal and longitudinal energy surfaces are uniform in most of the country indicating a weak cloud modulation of the radiation field denoting the so-called "dry season". The maximum value is found during April. The exception is presented at the northern part of Mexico where maximum values are reached during June and July. The other pattern of solar irradiance flux is presented from May to September, coincident with the rainy season and frequent cloudiness; the isopleths show distorsions and nodes particularly over the sierras. September reaches the minimum values; these results indicate modulation of the radiation field by an enhanced clouds amount and atmospheric water vapor absorption. As a consequence of this distribution, it is found a latitudinal solar irradiance gradient such that $\partial E/\partial \phi \geq 0$ occurs during the dry season. The condition $\partial E/\partial \phi \leq 0$ is fulfiled during the wet season. These facts indicate polewards transport of energy during spring and summer through a fine combination of astronomical and geographical parameters, i.e, a longer sunshine duration and absence of clouds during summer at the northern part of the country, whereas the southern part is strongly modulated through the constant presence of clouds reducing the incoming radiation flux.

Finally, it is shown that the geographical distribution of the solar radiation flux strongly depends on the irregular relief of the country.

1. Introduction

In recent years most National Meteorological Services have experienced an increasing demand for solar radiation data. The demand comes from a variety of users, such as solar energy industry, agriculture, architecture, hydrology and the climate community.

The use of solar energy ranges from space heating and cooling to solar electric power generation and photosynthetic fuel production.

The solar radiation statistics required in the designing, simulating, and scaling of solar systems, as well in the evaluation of the solar resource at a given region are: Knowledge of the solar irradiance components (global, direct, diffuse); distribution on a horizontal plane or and on an inclined surface; spatial and temporal distribution for scales that span from few kilometers (crop production models) to on various time scales, and the spectral distribution.

Ground observations by well-trained specialists, and quality control systematic radiometric calibration and maintenance are usually lacking. Financial support needed to set up an ideal surface-based network that could report on the microclimatic details of solar energy resources would be very high.

In Mexico, there has being a sustained interest to assess the solar resource of national basis. Due to the scarceness of solar radiation stations, most of the estimates are based on relationships of the form $Q/Q_o = a + b\ n/N$ (Ångström, 1924) where Q is the estimate of solar global irradiance; Q_o is Angot's value; the ratio n/N is the percentage of possible sunshine; a and b are regression coefficients, (Almanza and López, 1975; Galindo and Chávez, 1977; Jáuregui, 1978). An attempt to using cloudiness determined by photointerpretation of satellite pictures was reported by Hernández (1976). The results obtained show considerable differences of the order of 20% (Velázquez *et al.*, 1988). These discrepancies are due to following factors: Number of stations and length of the record used; value of the solar constant Q_o, and the particular methodology used. Galindo and Chávez (1977), have used a considerable number of solar radiation stations from measurements of thermoelectric pyranometers periodically calibrated. Almanza and López (1975) have used other parameters such as latitude, number of rainy days and, relative humidity.

Methods for assessing solar energy resources from satellite observations have made great progress. There is strong evidence (Beriot, 1984) that meteorological satellites are an invaluable tool for solar radiation assessment. They can provide high resolution both in time and space and cover areas of the Earth for which there is little or no information.

Satellite methods can benefit from ground networks of solar radiation observations of high quality that can serve as ground-truth for validation of satellite-derived irradiances.

In this report we present results of satellite derived solar irradiances on different time scales for the Mexican Republic.

2. The satellite and sensor

The data used in this work were derived from the radiometers mounted on the two geostationary meteorological satellites (SMS-2/GOES-2) which were fixed over the equator at 75°W and 135°W, respectively, at an altitude of about 37,500 km. The sensor is a visible and infrared spin-scan radiometer (VISSR) instrument that provides observations in the infrared (IR) spectrum (10.5 to 12.6 μm) and in the visible (VIS) spectrum (0.55 to 0.75 μm). The satellite GOES-2 (East) has acquisition times on the hour and selected half-hour pictures with a coverage of 50°N - 50°S and 25°W - 125°W. The SMS-2 satellite (West) acquires information 15 minutes after the hour and selected 45-minutes after the hour pictures. Its coverage is between 50°N - 50°S; 85°W - 175°E (Bristor, 1975).

3. The satellite data

The digital visible data used in this work were collected at the National Environmental Satellite Service, NOAA between June 1982 to December 1984 at a resolution of 8 km. It is part of a larger VISSR data base (VDB) used in a NOAA project which objectives were to explore the feasibility to determine solar irradiances at the ground from satellites and supplementary surface data (Tarpley, 1979; Justus and Tarpley, 1984).

Solar irradiances at the ground determined for Mexico for the period July 1982-December 1984 using the statistical method of Tarpley (1979) constitute our final data set which was kindly provided to us by Dr. J. D. Tarpley from NOAA.

4. Methods

4.1 Data Management

Satellite-derived solar irradiance data for Mexico with period July 1982-December 1984 were storaged in magnetic tapes of density 2,400 bpi. Format analysis (code, bits per byte, block size and maximum recording size) was made using the utility SYSTEM/DUMPALL.

The information was brougth from the magnetic tapes into the hard disk of the Burroughs 7800 from the University Computer Center. The new format used is EBCDIC, 6 bits and also fix format. To pass from the density of the original computer to the Burroughs density it was prepared an algol software with bits handling per word. Furthermore, the information was split into n-archives storaged using the normal Burroughs procedures. Finally, in order to handle the information in personal computers, the archives were pass through the kermit software into 5 1/4" floppy diskettes. The archives consist of seven daily digital images or "pictures" which cover most of the Mexican territory (90-110°W, 16-30°N) accessed from GOES-East at different zenith angles, i.e., sampling times (1300, 1500, 1700, 1800, 1900, 2100 and, 2300 GMT).

Let i denotes the rows of a matrix such that $90 \leq \mathrm{i} \leq 110$, and j denotes the columns such that $16 \leq j \leq 30$, then the matrix $D_k(X_{i,j})$ represents the k-image, i.e., $1 \leq k \leq 7$. A point (i, j) means a point of longitude-latitude (Φ, ϑ) on the array.

The daily mean of solar irradiance (global solar radiation) is obtained through the average:

$$M_{i,j} = 1/n \sum D_k(i, \; j) \tag{1}$$

where n is the number of days.

In a similar way it is obtained the seasonal mean $E_{i,j}$

The mean value of each image for any point on the array is obtained through the integration

$$I_{\vartheta,\Phi} = \int m(i,\ j) di\ dj \qquad (2)$$

The units of I are MJ/m^2.

4.2 Preparation of the climatological charts

Global solar radiation data on different time scales (hourly, daily, monthly and seasonal) were plotted on charts of Mexico, each chart consists of 21×15 longitude-latitude points.

As a guide for the design of the radiation isolines the software "Surfer" was used. The isolines drawn were analysed using as template a map of the physiography of Mexico. It was found that the paths of the isopleths run quite closely with the relief.

Since the model calculation ends at 30°N, it was necessary to estimate the paths of the isopleths for the rest of the northern part of the country, taken as reference the work of Galindo and Chávez (1977). These authors have assigned the Ångström's derived coefficients in accordance with the modifications made for the case of Mexico to the Koeppen's climatic classification system (García, 1973). For the southern part of the country, i.e., the Yucatán plains, the isopleths were easily extended since there topography is quite regular and smooth.

The solar irradiance field is also analyzed using the software Surfer in order to produce latitudinal (t, ϕ, E) and longitudinal (t, ϑ, E) distributions. Here E denotes the mean monthly global solar irradiance, t the month of the year, ϕ and ϑ, the latitude and longitude, respectively.

4.3 Error of estimate for mean daily irradiances

The coefficients that enter into the model to determine solar irradiance at the surface from satellite data were obtained by Tarpley (1979), for the region of the Great Plains in the United States. In order to have an estimate of the errors generated when using this model in other latitudes with different surface properties (albedos) and climatological conditions one of us (Galindo, 1987), has validated the satellite monthly estimates of global solar radiation for Mexico and Uruguay against ground-thruth data obtained from calibrated pyranometers during two years, namely 1982 and 1983. The results of the validation show standard errors less than 10%.

Other validation test was performed for the satellite-derived insolation for 1984. The satellite-derived irradiances were compared against pyranometric data measured in Mexico City obtaining an standard error ranking between 3 to 5% (Galindo, 1987).

5. Results

5.1 Geographical Distribution of Global Solar Irradiance

Figure 1 shows a three-dimensional diagram of global solar irradiance generated as a function of latitude for 1984.

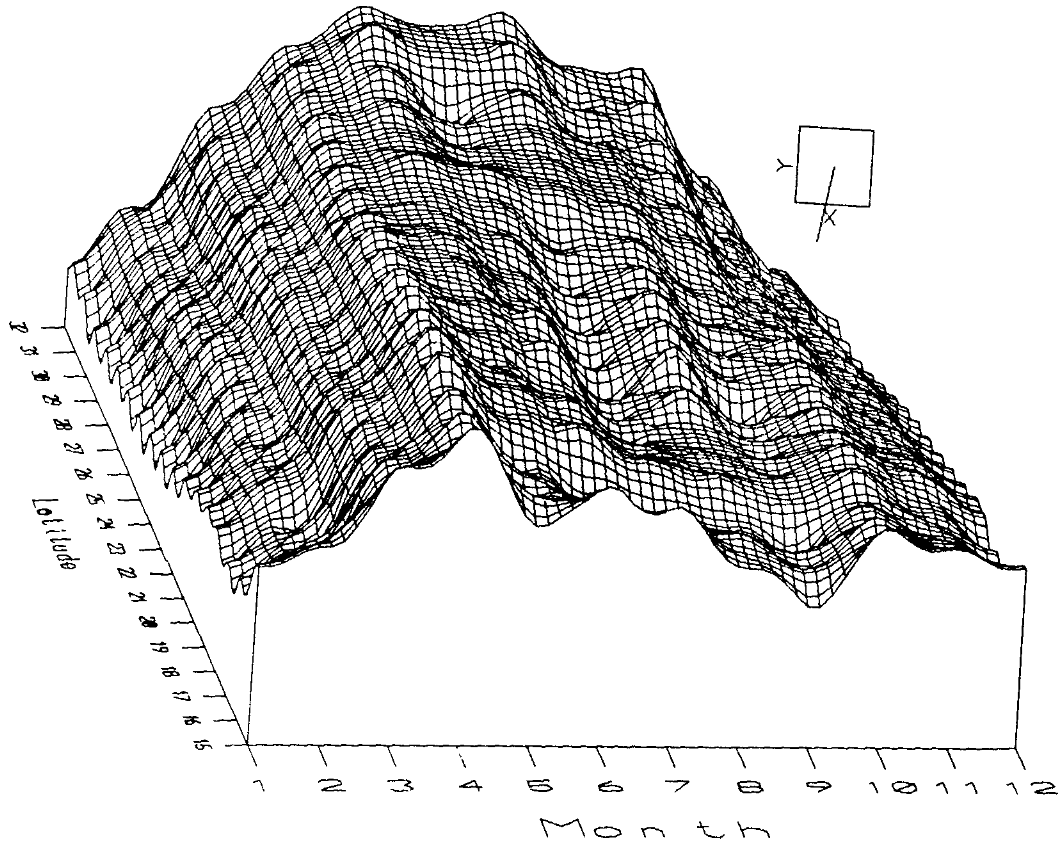

Fig. 1. Tridimensional surfaces of mean monthly values of global solar irradiance for Mexico as a function of latitude.

The main features are: The existence of two well-defined patterns, namely from October to April the solar irradiance surface is quite regular; it goes down smoothly from October to December in most parts of the country except at the northeast part where it descends more abruptly. From January to May, solar irradiance intensity goes up steadily in most parts of Mexico to reach the maximum values during April, however the northern part of the country reaches its maximum until June.

Since the atmosphere is relatively dry from October to April, atmospheric water vapor absorption is reduced and clouds are not in enough quantities to modulate the incoming solar irradiance. There is an inverse correlation between water vapor content and global solar irradiance. The mean monthly value of water vapor tension falls from 14 to about 8 mb. Whereas in May, when precipitation "normally" starts the mean water vapor tension is at our latitudes, around 11 mb (Galindo, 1987).

The other observed pattern on the solar irradiance surface runs from May to September. It is seen as a series of depressions and combs distributed from the center of the country down to the southern part (18 to 13°N) where it reaches the minimum energy values, particularly during September. This portion of the country is really located within the tropics and it is dominated by heavy cloud layers together with intense precipitation (Mosiño and García, 1973; Galindo, 1989). The Mexican Plateau (19 to 23°N) with an average elevation of 1,500 m above sea level (Mosiño and García, 1973), shows depressions of the solar irradiance surface which tend to vanish northwards. Next, there is a region between 24 to 27°N where it is seen an important depression, particularly during June. However, in the northern part of the country (28 to 33°N) there is almost no reduction of the incoming solar flux during June and July, but exists some in August and September although smooth. At this latitude the precipitation regime is mostly Mediterranean (Wallén, 1956), therefore clouds modulation of the radiation field should be more important during winter time. The above results indicate that in most of the country, during May to September, the solar radiation field is strongly modulated by clouds and water vapor absorption. In fact, the mean montly water vapor tension ranges from 11 mb in May to slightly more than 14 mb in September (Galindo, 1977).

The above described physical conditions give place to the existence of a latitudinal gradient of global solar irradiance $\partial E/\partial \phi$.

The condition $\partial E/\partial \phi \geq 0$ is found during the dry season months whereas $\partial E/\partial \phi \leq 0$ is present during the wet season which corresponds to spring and summer.

The two effects above described indicate a fine combination of the main modulators of the radiation field, firstly, the presence of clouds and enhanced water vapor absorption during the months of May to September, most of these clouds are developed over the mountains by convective processes giving a close daily relationship between precipitation and cloud formation modifying in an important amount the incoming flux of solar irradiance. In fact, most of the meteorological elements in Mexico are under the control of the orography (Mosiño and García, 1973), solar irradiance would not be the exception.

But the important feature that comes out from this combination of a very irregular mountainous underlying surface and its interaction with the physical environmental parameters is that during spring and summer, the solar incoming flux is reduced at the southern part of the country, simultaneously it is incremented on the northern part in two forms: Much less clouds amount and longer sunshine duration. Through these combination of geographical and astronomical mechanisms it is explained the existence of a negative latitudinal gradient of solar irradiance. The condition $\partial E/\partial \phi \leq 0$ clearly indicates a direct polewards gradient of energy.

Other geographical factor that determines the climate of Mexico is the orography, according with Mosiño and García (1973), more than 50% of the Mexican land areas is found above the 1,000 m contour line, therefore it is necessary to study the solar irradiance as a function of the relief. To do that it is presented Figure 2 which it starts at the Yucatán Peninsula and ends at the Baja California Peninsula, i.e., it goes from southeast to northwest.

The initial part of the surface corresponds to the Yucátan Peninsula, here January and February receive a quite regular flux of solar irradiance, than in March there is a sudden increment which it reaches a plateau that stays during April and May. From June to September there is a smooth solar irradiance decrement indicating a scarce clouds amount. The months of May to September show a large depression of the irradiance surface from 95 to 98°W down to the east coasts of Mexico where the minimum values are found (portions of Veracruz, Tabasco and, Chiapas) extending through the Mexican Volcanic Axes. From 99 to 105°W the Mexican Plateau, with an average elevation over 1,500 m above sea level shows during these months a more regular and not so diminished solar irradiance pattern. However, at the center of the country, from 106 to 110 W, the solar irradiance surface depression of the wet season is more pronounced, perhaps due to the influence of the Sierra Madre Occidental, roughly oriented from north-northwest to south-southwest. The northwestern part of the country from 110 to 115°W, shows a different distribution of solar irradiance, summer months reach the maximum values, particularly June and August, then after September there is a systematic decrement of solar irradiance that reaches the minimum values between December and January.

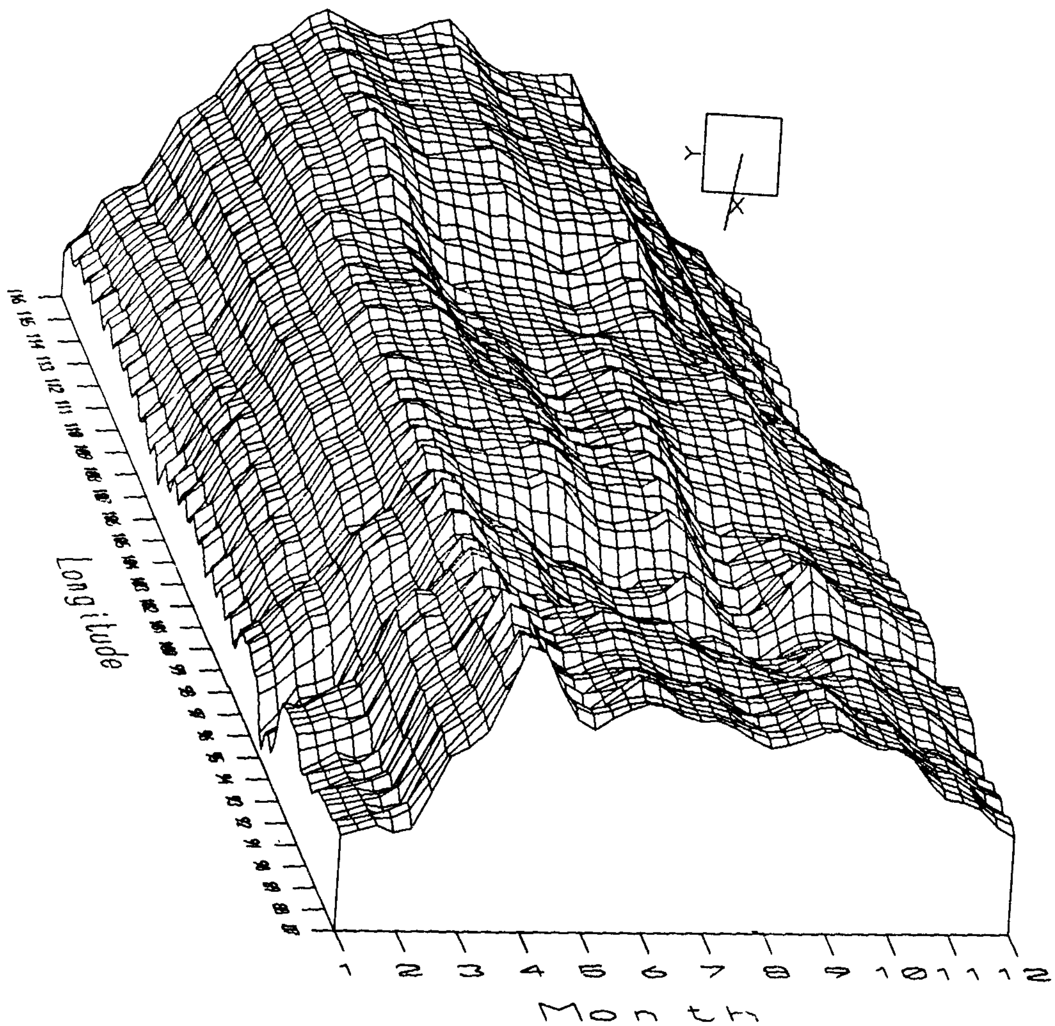

Fig. 2. Tridimensional surfaces of mean monthly values of global solar irradiance for Mexico as a function of longitude.

Finally, it is also seen that the Pacific Coastal Plains receive more solar irradiance during the whole year than the Gulf Coastal Plains.

The findings here reported indicate that the abrupt relief of Mexico, together with the presence of synoptic systems, such as the seasonal migration of the Intertropical Convergence Zone; the easterly waves in summer and, the so-called "Nortes" in winter, modulate the solar irradiance field of Mexico through convective activity and moisture invasion from the Pacific and Atlantic Oceans.

5.2 Climatological Charts of Mexico

The results are also presented as climatological charts. The mean monthly charts have being constructed for each month of the year. Here are presented only charts corresponding to maximum and minimum values, namely for April and September. These months are representative of the dry and wet seasons, respectively. The whole set of monthly charts will be published elsewhere (Galindo and Valdés, 1990).

Mean seasonal solar irradiance charts for Mexico have also being prepared and they are part of the Atlas Nacional de México from the Instituto de Geografía of the National Autonomous University of Mexico (Galindo *et al.*, 1990).

In what follows we discuss the climatological features found on the solar irradiance field for Mexico during April and September of 1984.

Figure 3 shows the mean monthly values of global solar irradiance for April as derived from the satellite-measured data:

The highest values are found on the Pacific Coastal Plains, particularly from part of the coasts of Oaxaca, Guerrero, Michoacán, Colima, Jalisco and the southern part of Nayarit, also maximum values are depicted on the plains of the Yucatán Peninsula. The Mexican Plateau, together with the center and northern part of Mexico including the Baja California Peninsula show secondary high values. The minimum values are found in the northern part of the State of Veracruz where the isopleths tend to be quite narrow. The solar irradiance latitudinal gradient is positive.

Figure 4 shows the mean monthly values of global solar irradiance for September as derived from the satellite-measured data:

The maximum values are found on the north-western part of the country, namely part of Chihuahua, Sonora, Baja California and Sinaloa together with the Yucatán Peninsula. The Mexican Plateau shows very variable values, particularly around the Mexican Volcanic Axes. Minimum values are found through the States of Tlaxcala, Hidalgo, Puebla, Veracruz and the southern part of Tamaulipas towards the Gulf Coastal Plains.

The irregularities of the isopleths and the presence of minimum values around the mountains and sierras are indicative of convective activity and an enhanced clouds amount, particularly from the center towards the southern parts of the country. Finally, the latitudinal gradient is slightly negative.

Finally, Table 1 shows the satellite-derived mean monthly values of global solar irradiance for the capital cities of Mexico.

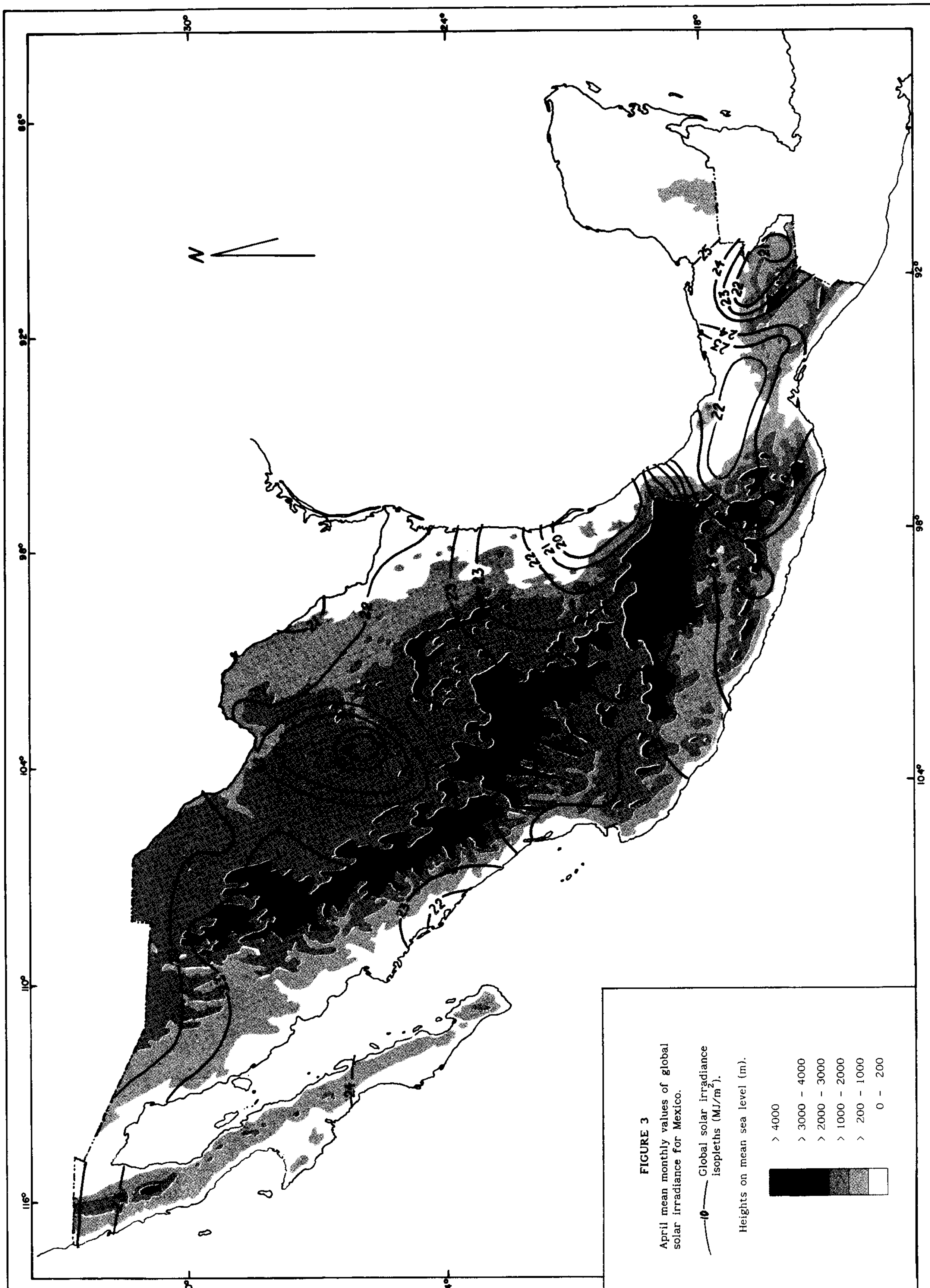

FIGURE 3
April mean monthly values of global solar irradiance for Mexico.

10 —— Global solar irradiance isopleths (MJ/m^2).

Heights on mean sea level (m).

> 4000
> 3000 - 4000
> 2000 - 3000
> 1000 - 2000
> 200 - 1000
0 - 200

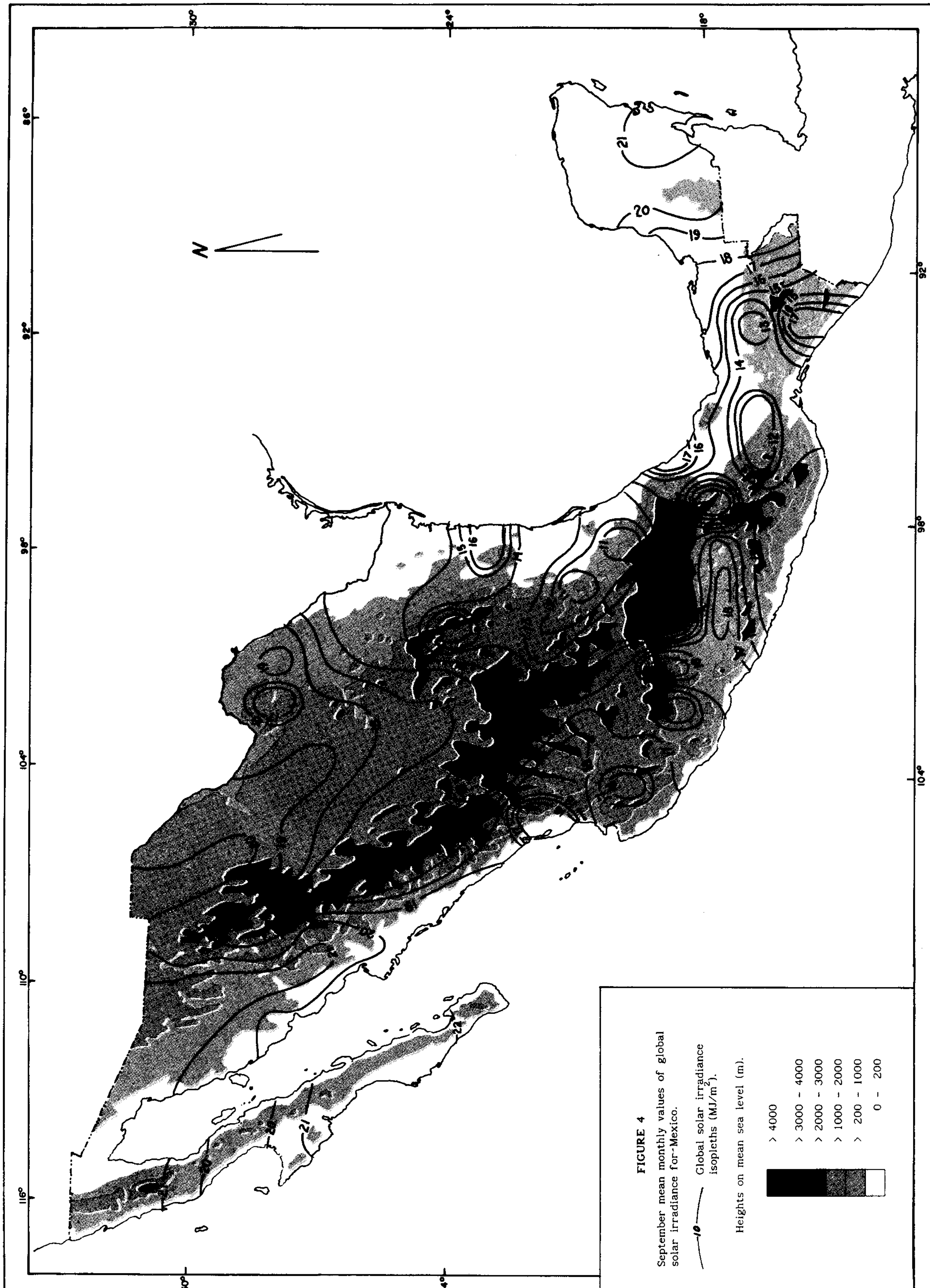

FIGURE 4

September mean monthly values of global solar irradiance for Mexico.

TABLE I.
SATELLITE-DERIVED GLOBAL SOLAR IRRADIANCE VALUES (MJ/m^2) FOR THE MAIN CITIES OF MEXICO

C I T Y	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
AGUASCALIENTES	14	16	20	20	22	21	16	19	16	19	17	14
CAMPECHE	14	14	19	25	19	21	20	18	19	18	16	14
CIUDAD DE MEXICO	15	18	21	24	21	19	15	14	13	18	18	16
CIUDAD VICTORIA	8	14	18	22	21	23	21	22	15	16	14	12
COLIMA	15	19	22	24	24	21	17	19	16	19	18	16
CUERNAVACA	16	19	22	24	22	21	18	15	15	19	18	16
CULIACAN	12	17	20	22	24	20	17	19	19	18	16	11
CHETUMAL	14	13	20	25	18	20	19	18	21	18	17	13
CHIHUAHUA	10	14	18	23	22	21	21	20	19	18	14	10
CHILPANCINGO	15	19	23	24	21	17	17	17	14	18	17	17
DURANGO	12	17	20	23	22	19	14	17	16	18	15	13
GUADALAJARA	14	18	21	25	23	19	15	18	17	18	17	15
GUANAJUATO	14	17	20	23	22	20	16	18	15	18	17	14
HERMOSILLO	11	15	19	23	25	23	23	20	21	16	12	9
JALAPA	9	13	19	23	22	19	17	19	15	18	15	13
MERIDA	14	14	19	25	20	22	20	19	20	18	16	14
MEXICALI	11	14	19	22	24	23	24	21	21	16	11	8
MONTERREY	8	15	18	22	20	22	20	21	15	12	12	10
MORELIA	15	18	21	23	23	21	18	19	17	18	18	15
OAXACA	14	16	20	23	19	16	14	17	13	19	18	15
PACHUCA	14	16	19	22	18	18	15	17	13	17	17	15
PAZ (LA)	13	17	21	24	26	22	23	22	21	17	14	11
PUEBLA	15	17	22	24	21	20	18	18	15	19	17	14
QUERETARO	15	17	20	23	20	19	15	17	13	18	18	14
SALTILLO	9	15	20	22	21	22	19	20	15	15	13	12
SAN LUIS POTOSI	12	15	19	23	21	22	15	18	12	16	15	12
TEPIC	13	18	21	24	24	22	16	20	18	19	17	15
TLAXCALA	15	17	19	23	20	18	17	17	15	19	17	14
TOLUCA	15	18	21	24	21	18	15	14	13	17	18	16
TUXTLA GUTIERREZ	14	16	21	24	18	20	20	16	14	18	17	16
VILLA HERMOSA	12	13	19	23	20	20	19	19	16	18	16	14
ZACATECAS	14	16	20	23	22	21	16	19	16	19	16	14

6. Conclusions

Satellite-derived solar irradiances are very useful since they can provide an assessment of the solar resource of variable spatial and temporal coverage.

The statistical model of Tarpley is applicable also to other latitudes as is the case of Mexico. The comparison of the estimate with ground-thruth data gives a standard error of 3 - 5%.

The representation of the distribution of the global solar irradiance over Mexico using tridimensional surfaces as function of latitude and longitude give insight on the relationships between the astronomical and geographical factors that intervene in the modulation of the solar radiation field. During spring and summer, there is a polewards gradient of solar irradiance latitudinal gradient which changes in sign during fall and winter.

The solar irradiance field is distributed in Mexico with two distinct patterns:

From October to April most of the country receives the largest amounts of solar irradiance, reaching the maximum values during April. It is only at the northern part of the country that maximum values are found in June. This irradiance pattern is coincident with the so-called "dry season".

From May to September, coincident with the rainy season, the solar irradiance field is strongly modulated by clouds and water vapor absorption in most of the country.

In general the highest irradiance values are found at the north-western part of the country, at the Yucatán Peninsula and Baja California and on the Pacific Coastal Plains. The minimum values are found on the Gulf Coastal Plains, and the States of Tlaxcala, Hidalgo, Puebla, part of Veracruz, Tabasco and Chiapas. The Mexican Plateau shows variable values, particularly over the Mexican Volcanic Axis.

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