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Research Article

Treatment of Data and GIS Implementation of Solar Radiation and Temperature Maps: Example in South-East of Spain

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This paper presents the maps of solar radiation on the surface of south-east region of Spain named *Región de Murcia*. These maps are the result of treatment, study, and correlations obtained by data of 35 weather stations distributed throughout the region. These stations have collected data for 6 to more than 25 years. The paper presents the work performed for the treatment of collected data, the correlations used for the adjustment of the data, and the parameters obtained as a result of this adjustment. The weather stations are equipped with various sensors to collect several parameters, the measures covered and used for the study were global and diffuse radiation (in case that the station has pyranometer diffuse) and ambient temperature. The results were used to produce maps of horizontal radiation (global and diffuse) and ambient temperature at the surface of the region studied. To achieve the irradiation maps for this extended region has been used "*r.sun*" program, technical program that with the help of GRASS program uses geographic information systems (GISs) to evaluate the influence of geographical variables captured on horizontal plane at the surface. Using the results of the program for theoretical data and/or generic, and with the feedback obtained by the correlations of measures covered from weather stations, we have studied the incident radiation on the region. The main result of this study was to produce maps of irradiation on horizontal plane, correction for inclined surfaces, and also maps of temperature of the studied region. On this basis, results have been produced maps and tables of monthly solar radiation (mean maximum and minimum) for each of the 45 municipalities of the Region of Murcia. Thus, was obtained a useful tool for the calculation of available energy and thermal needs at the design process of plants using solar thermal and photovoltaic.

1. Introduction

The energy from the sun is responsible for the vast majority of the types of energy that transforms and use the humanity. Besides, this source of energy is inexhaustible on a human scale, so solar energy has a special place in the field of renewable energy.

To enable the collection and use of solar energy is necessary to make a well-designed catchment facility following a series of theoretical and technical criteria, right inclination to Ecuador, design of solar tracking systems, correct choice of materials to be used by recruiters, and so forth. An important parameter for the evaluation and implementation of feedback systems is undoubtedly to know with accuracy and reliability solar energy incident on the site to be exploited. The European Economic Community (EEC) has spent years talking about the documentation of areas as susceptible to the so-called "solar farm" [1–3], this documentation has been made based on the potential available energy of the sun for each region. Several countries of European Community have developed their own irradiation maps and model using different tools, for example, using images from Meteosat [4] to obtain the solar irradiation of Italy. Similar works are possible to find in the literature for other parts of the Earth, for Africa [5], South-America (Brazil) [6], New Zealand [7], Asia (Thailand) [8], and so forth.

For the realization of solar radiation atlas, there are numerous references, where it is described the theoretical basis and relevant statements. The main reference in Spain has been the *Solar Radiation Atlas of Spain* [9] conducted by the National Meteorological Institute (INM). It is also possible to find updated maps of solar radiation in the "situation reports" from the Ministry of Environment of Spain, published on its website and endorsed by the Institute Meteorological Institute. On the other hand, there have been several Spanish autonomous communities that have made their own solar maps and/or climate maps. The review shows some examples of communities radiation maps, for example, [10–16].

Region of Murcia shows a huge potential in the field of renewable energies, especially solar energy. This is evidenced by the growing interest of companies to install solar systems (thermal and photovoltaic) in many municipalities of the region. Therefore, this the elaboration of a detailed atlas of solar radiation for this region.

In addition, during the development of this work, the development work will explain research techniques of processing and interpretation of available data of insolation and temperature of the different weather stations installed in the Community *Region of Murcia*. This work has also included a series of maps of average air temperatures, always with the objective of being useful to predesign solar systems, by capturing heat and/or photovoltaic or through the use of bioclimatic architecture.

2. Objectives of This Work

The use of solar energy is limited mainly by two features: the intensity of solar radiation received by Earth, which in turn depends on daily and annual cycles and the latitude of the application on the land surface, weather conditions, and prevailing weather.

Therefore, the use of solar radiation as an energy source requires knowledge of the amount and distribution of incident solar radiation on a particular place and its temporal variation over the annual and daily cycles.

The incident solar radiation on a given region is usually represented on maps of monthly and annual solar radiation. The most common procedure to design these maps is through interpolation, extrapolation of time series of measures of insolation on the surface, took by pyranometer in specific geographic locations.

With the use of these maps is possible to assess the viability (or nonviability) of the location of a particular of solar-energy plant (thermal or photovoltaic). Actually, these maps could be used to catalog areas as susceptible (or not) to be used as "solar farm."

The aim of this work is to develop a map of mean solar radiation received on horizontal surface (global and diffuse solar irradiance at ground on a horizontal surface), conversion factor of declination surfaces and, also, to obtain a map for the average air temperatures at the surface level, for the Region of Murcia.

3. Acquisition and Sources of Data

Nowadays, there are three options to assess the evolution of terrestrial solar radiation data in order to do some climate analysis or to make a forecast of the irradiance or irradiation in a particular place.

(1) To use databases of solar radiation on the specific place site and make forecasts based on past experience of the site. These forecasts will be more reliable when the database is temporarily longer. This possibility is not feasible because it would require the installation of monitoring stations in all those sites susceptible to use for solar projects.

(2) To use mathematical models, more or less complex, of behavior of atmosphere of the Earth's, that allows obtain correlations between ground data and known data of the extraterrestrial radiation.

(3) Using a combination of mathematical-statistical interpolation and extrapolation, that with the help of

   (i) irradiation data in nearby sites,
   (ii) combined with other data (geographical, climatic, turbidity, etc.),
   (iii) with calculated extraterrestrial radiation,
   (iv) and applying contrasted mathematical-statistical models,

   it is possible to obtain a good estimation of the horizontal irradiation values in a particular place.

First option is totally unworkable because of the great number of measurement stations and time required to make a reliable database.

The use of mathematical models mentioned on the second point require an extensive study is beyond the scope of this text. Besides, it would be necessary to model a large number of climatic variables. There are several mathematical models in the literature that use different methods, such as neural network [17, 18], other mathematical technics [19–21], or using indirect measurements from satellite [4, 8, 22].

Mathematical/statistical models, referred to the third point, will be used in this study to carry out the solar maps of the South-Est region of Spain. These models are not exempt from the use of measured data and, of course, the larger the database used the more reliable the response of the model. The use of these kind of models is very useful as showing the papers found in the literature as [7, 23–29].

3.1. Measuring Stations. Murcia is located at the south-east corner of Spain, it is limited by the Mediterranean Sea to the south, by the Valencia Community to the east, by Castilla-La Mancha to the north, and by Andalucia to the west. The major part of the region is influenced by the Mediterranean weather but the north-west of the region has a partial influence of continental weather due to the proximity of the high Iberia plateau. Figure 1 shows the situation of Murcia in the Iberia peninsula.

Today there is availability of terrestrial solar radiation data from monitoring stations grouped in more or less organized networks. In particular, for this work, the Instituto

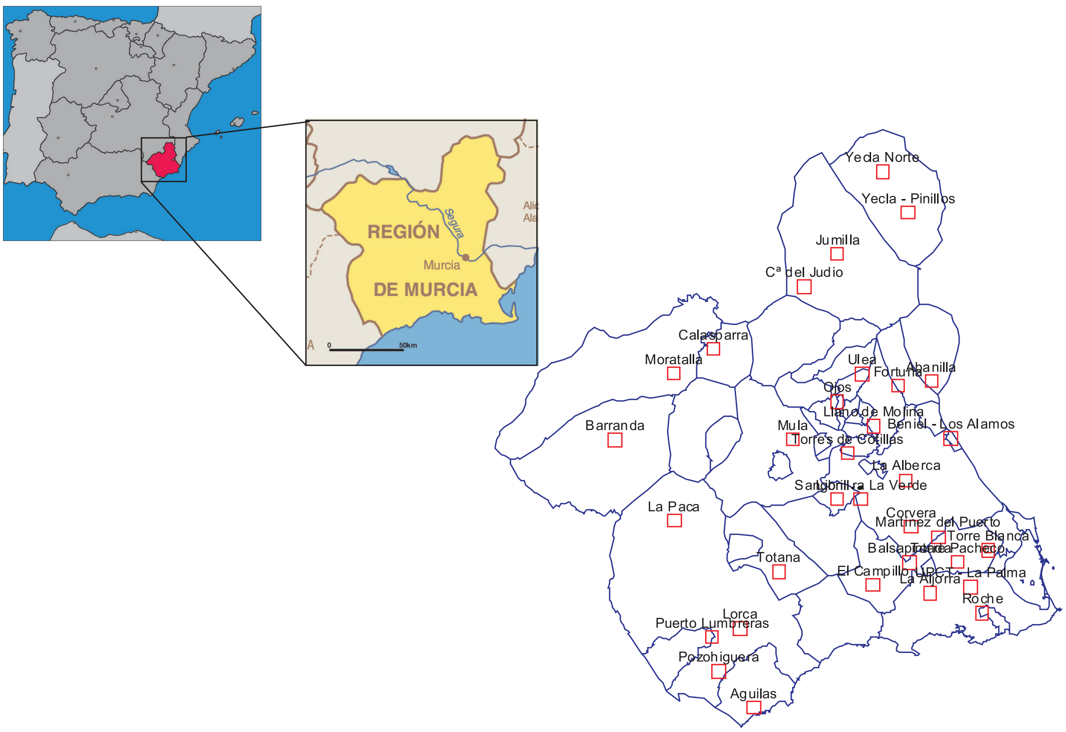

FIGURE 1: Situation of Murcia's region in Spain. Arrangement of the measurement stations in the territory of Region of Murcia.

Murciano de Investigación y Desarrollo Agrario y Alimentario (IMIDA) has more than 100 measuring stations spread over the length and width of Murcia's Region, and more than 30 of these stations have some system of measuring of solar radiation. Some of these stations are collecting data from more than 10 years ago. For this study, have been used data from IMIDA and data from *Instituto Nacional de Meteorología* (INM) that have irradiation data with more than 25 years.

Figure 1 shows the spatial arrangement of the stations on the map of the Murcia's Region: a list of the codes of the stations with the data population of eachone, the exact position of its location (in UTM coordinates and altitude above sea level). More detailed information of the stations can be found at the web address of IMIDA http://imida.es/.

3.2. Treatment of Measured Data. All data collected were subjected to a treatment process to control the quality of the measurements. All field measurements are exposed to multiple sources of error, since the measurement itself until the inclussion in the database. Measurement errors must be eliminated in order to use these data with enough reliability.

In order to detect and reject data with high probability of error a similar method to [10, 11] have been used. This method was developed by Baldasano et al. [10] for the realization of Atlas of solar radiation in Catalonia in 2001. This method involves the analysis of records based on two criteria, temporal and spatial coherence. These two criteria are complementary and they have been interspersed in the process of data cleansing.

Firstly, we plotted the data series available for each station and for all years monitored. An example of these graphics is shown in Figure 2. Once all data have been represented, outliers values in the curve of radiation that spread in excess are directly removed from the data series. Figure 2 shows the marked circles dismissed some of the data series.

Secondly, the data are compared with the annual curve of maximum radiation at sea level, and all the excess data are dismissed. This process will be explained in detail in following sections.

The spatial selection is done as follows. If two nearby stations provide very different data, the data are compared with a third station near both, and the disparate data are rejected or adjusted.

Each weather station has been recording data during a different number of months and some of them has been operating less than two years. The simultaneity of the data, the number of data available for each station, the proximity of the stations, maintenance of measuring devices, and so forth are an important factor to have an acceptable level of data reliability and performance.

3.3. Collection of Several Necessary Data. In this work, the surface temperature data were collected in order to make a map of temperature of the region. These data and maps are very useful to obtain a good prediction of the energy that could be produced by installations with thermal collectors or PV panels, and also to predesign and consider some special tasks necessary for an specific installation. Data were

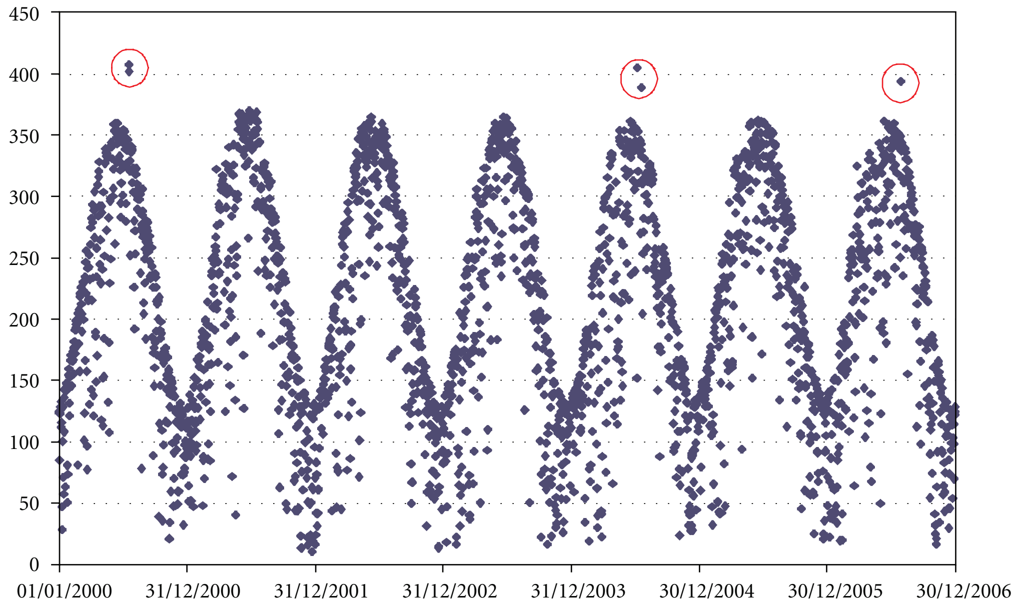

Figure 2: Graphical representation of radiation data from a weather station of Lorca. Data marked with red circle are rejected during the first debugging process.

collected from the same meteorological stations. The characteristics of temperature sensors used can be found on the website of IMIDA.

Additionally, in order to do a correct treatment of the data and to correlate them with the results of the widely used radiation models, is needed to quantify several parameters, such as the following.

(i) *Linke factor*. This factor quantifies the turbidity of the air, Figure 3. This factor is important to properly quantify and model phenomena such as absorption and scattering of solar radiation experienced by the solar radiation to pass through the Earth's atmosphere [30]. This factor is quantified on a monthly basis by the SoDa "Services for Professionals in Solar Energy and Radiation" and can be obtained according to the appropriate coordinates from web site http://www.soda-is.com/. This factor is necessary to evaluate the total radiation with models which do not have enough data and number of measure stations. However, with the data used in this study is possible to avoid the Linke factor because the data have the effect of turbidity included. In this study, Linke factor was only used in the creation of the first maps, just with thoretical models.

(ii) *Frequency of sunny skies*. An important parameter to process irradiation data correctly frequency of sunny skies. This data can be found in the database servers from satellites. It is the percentage of probability for each month according the latitude and longitude of the place. A square interpolation was made to obtain a valid average value of this parameter in the Region of Murcia. Table 1 shows the results obtained from webserver http://www.satel-light.com/.

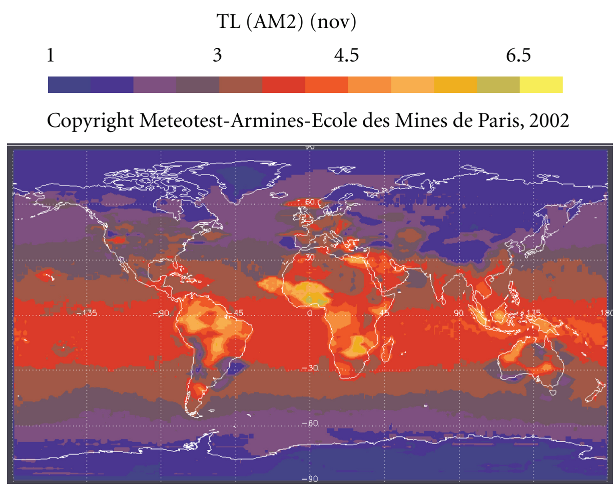

Figure 3: Factor of Linke turbidity factor of the atmosphere for the month of November worldwide. Source: SoDa "Services for Professionals in Solar Energy and Radiation. http://www.soda-is.com/".

(iii) *Sunshine hours per day*. This parameter is more interesting than the previous one, because it provides us with more information in a more direct way. In order these data could be useful must be collected directly from weather stations. During the process of obtaining data, it was found that only the INM weather station collects daylight hours, therefore, this information has not been used for realization of the maps, even though it will be used in a subsequent process of validation results.

On the other hand, to calculate and to do a correct treatment of irradiation data using GIS techniques is necessary

Table 1: Frequency of sunny skies for Region of Murcia and Linke factor for and specific meteorological station (Lorca). Source: "Satel-light Enterprise" (http://www.satel-light.com/core.htm) and "SoDa".

Month	Frec. of sunny days	Linke factor
January	58.8%	2.6
February	75.3%	2.9
March	70.5%	2.9
April	67.8%	3.6
May	66.0%	3.7
June	81.7%	4.1
July	89.7%	4.4
August	84.5%	4.3
September	70.6%	3.9
October	70.6%	2.8
November	67.1%	2.6
December	61.3%	2.2
Year	**72.9**%	**3.3**

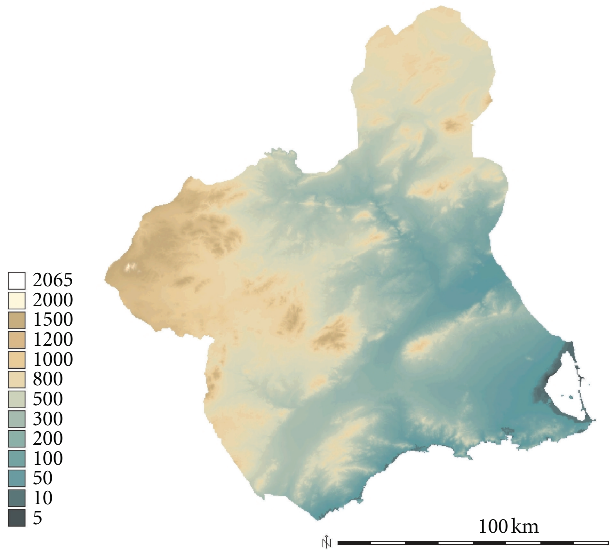

Figure 5: Altitude from sea level for Murcia Region.

Figure 4: Orientation of the land in Murcia Region.

to used other geographical data. This work has used the GIS program described in the papers [31, 32], this code is open source and is named GIS-GRASS and with the information of orientations and elevations. The package "*r.sun*" is able to recalculate the radiation map of a region as it is going to explain in following sections taken into account the geographical information. Figures 4 and 5 show the orientations and elevations maps for Murcia Region. These and other important data were obtained from various sources available on the Internet or publications from other more generic atlas.

4. Data Processing

The data treatment and its correct use are one of the most relevant parts of this paper. A proper data processing is associated with a pooling of data from different sources, a refinement, an adaptation of the data for use in models and GIS systems for a correct representation and interpretation, and so forth. Figure 6 shows a scheme of the process followed to obtain maps with enough reliability to be used.

4.1. Factors to Be Considered during the Treatment of Data. The solar radiation measured at a location depends mainly on the following factors.

(i) Astronomical factors: the decline and the distance from the sun to the earth vary throughout the year. These factors are easily quantified using the equations describing the translational motion of the earth to the sun, the equation of radiation is a function of the solar constant, 1367 W/m^2 (the value accepted by the World Radiation Center (WRC)) and the relative position of the measurement site to the sun (or whatever it is the same, the sun's declination and distance from Earth to the Sun, both are based on the day of the year).

(ii) Geographical factors: these factors are mainly the latitude and longitude of the place, it is necessary not to forget to measure the terrain and the altitude site because it may cause shadows and reflections that affect the measures and, therefore, irradiation available to the site.

(iii) Meteorological factors: defined mainly by the state of the sky. That is one of the most influential factors on the level and type of radiation available at ground level. The clear skys, generally provides greater proportion of direct than diffuse radiation. However, the

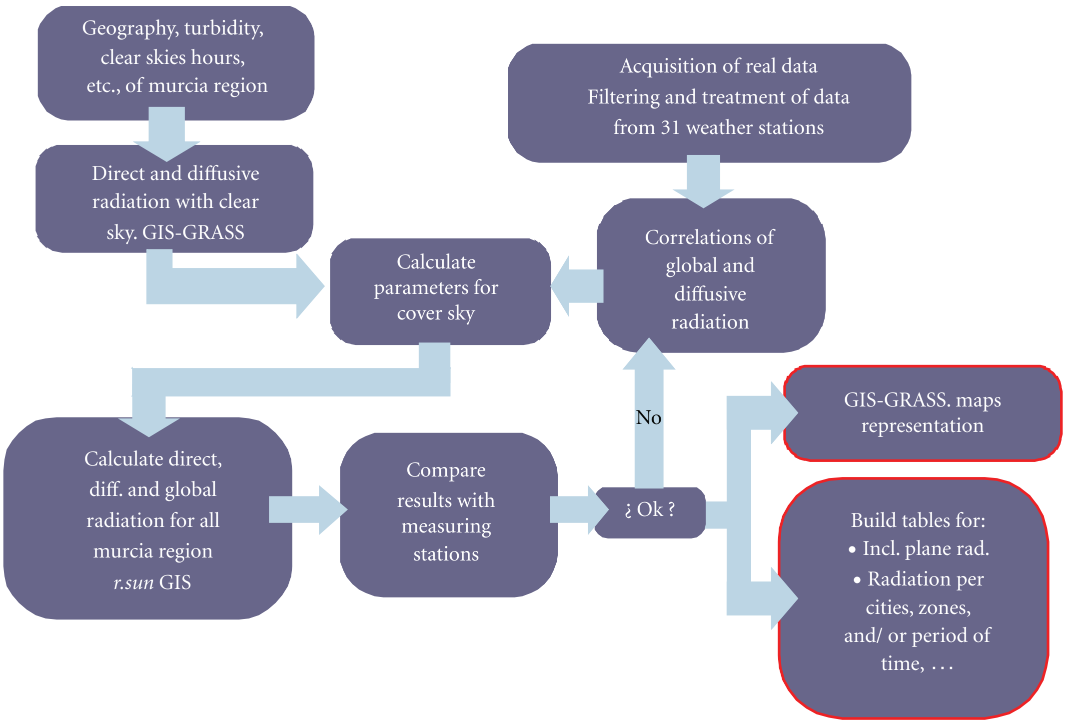

Figure 6: Global vision of the procedure. Methodology.

cloud covered and without shade indicates us that majority of the radiation received is of diffuse type.

Geographical factors are constant if the position of the measure stations does not change and the adjacent terrain clearance is not altered appreciably. The astronomical values are cyclical over the years and are sufficiently characterized by the equations defining the relative motion of the sun relative to Earth. However, meteorological factors in nature must be treated using statistical techniques because of its variable and unpredictable nature.

4.2. Model Used for Data Processing. The strategy for the treatment of data was similar to the one used by [10–12] in the creation of Atlas of solar radiation to Catalonia. In this case, the methodology is explained in Figure 6. The data processing was done by using a model that relies, in part, in the astronomical study of solar irradiance proposed by Santabàrbara et al. [33], and describes in the following paragraphs.

The data processing can be divided in three phases. The first step consists in obtain the daily radiation with clear sky at sea level, taking into account only the astronomical factors. The second phase consists of obtaining irradiation values implicitly by geographical and meteorological factors by adjusting parameters using statistical techniques. Finally the diffuse radiation is obtained by applying the Liu-Jordan model [34], a model widely contrasted and supported by the scientific community specialized in the analysis of solar radiation. These three phases of data processing are described in detail in the following section.

4.3. Obtaining the Global Radiation. Firstly, it was obtained daily clear sky radiation at sea level taking into account only the astronomical factors, "daily global solar radiation at sea level, where sky is always clear."

It has been calculated monthly average daily extraterrestrial radiation on horizontal plane, (1) and then applied to calculate the time dependence of the radiation at sea level using a simplified model for latitudes near the region of Murcia, (2), and compared the result with the time evolution obtained for all years of data collection in each of the seasons.

Monthly annual mean daily extraterrestrial irradiation, $\overline{H}_0$, is calculated as

$$\overline{H}_0 = \frac{24 \cdot 3.6}{\Pi} G_{SC} E_0 \left[\cos\varphi \cos\delta \sin\omega_S + \frac{\pi\omega_S}{180} \sin\varphi \sin\delta \right], \quad (1)$$

where G_{SC} is the solar constant, $1367\ \mathrm{W/m^2}$, ω_S is the angle of the sunrise correspond to a place with a φ latitude, δ is the solar declination for each day $\delta = 23.5 \sin((360/365)(D + 284))$, with the eccentricity correction $E_0 = 1 + 0.033 \cos((360/365)D)$, and D corresponds to the Julian day.

In case of clear sky and for mean latitudes, between 30–50 as the case of Murcia's region, the expression of daily mean irradiation at sea level, H_0 is possible to use and analytical expression, (2) which correspond to a simplified model proposed by Santabàrbara et al. [33]

$$H_0 = H_M + A_0 \times \cos\left[\left(\frac{2\pi}{365.25} \right) \times D + B_0 \right], \quad (2)$$

where H_M is the annual mean of the daily irradiation, A_0 is the amplitude of annual oscillation of the daily irradiation,

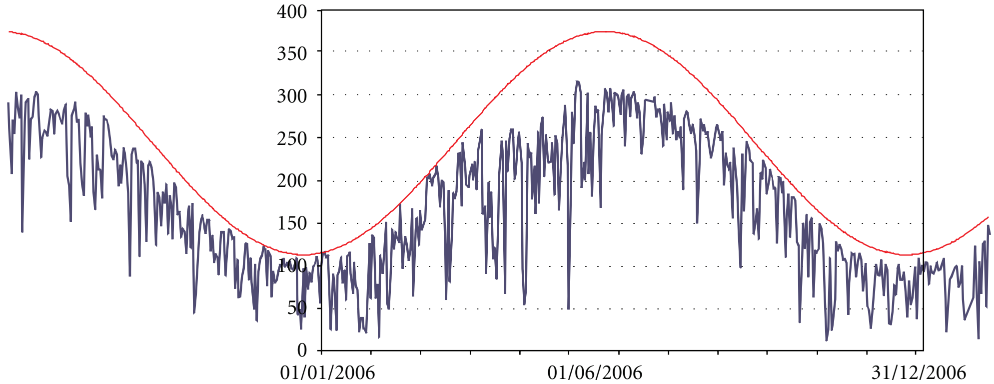

Figure 7: Example of the filtering process. Meteorological station of *UPCT-La Palma*.

and B_0 take into account the lag between the first of January and summer solstice.

It is important to note that (1) and (2) do not take into consideration any of the measured values, therefore, do not consider factors such geographical and/or weather, only regard the astronomical factors.

The curve generated by this expression is rather useful to discard the wrong values to the extent of irradiation on each of the stations. Figure 7 shows the comparison between the results measured in UPCT station at the campus of "*La Palma*" with the evolution of the irradiation by using (2). In case the data do not follow the analytical expression, the data are refused.

This methodology was used for all the meteorological stations. Simultaneously, the spatial coherence of the data has been studied from several provisional maps of irradiation, taking into account that the station in the neighbourhood of others should not record very different values from them. Combining these two coherence criteria, the filtering process applied has erased some periods of data. In any case, it was necessary to remove the complete data of an station.

4.3.1. Obtaining the Global Solar Radiation for Each Measurement Station. The next step was to consider an expression of the same type but obtained from the data measured in each of the measurement stations. Thus, the curve obtained will implicitly including geographical and meteorological factors under study site (meteorological station in particular). The expression used is

$$H = M + A \times \cos\left[\left(\frac{2\pi}{365.25}\right) \times D + B\right]. \quad (3)$$

Note that now H is the annual mean of the daily irradiation the average daily global irradiation on horizontal plane measures by a meteorological station, M is the annual average daily radiation for an specific location, A is the Amplitude of the annual variation of daily irradiation in the location, and B is the factor that corrects the gap caused by the calculation start on first of January for the site under study.

The parameters M, A, and B are unique to each station were obtained by an statistical adjustment througth the method of least squares differences using the database from each of the meteorological stations. In a set of measurement data, the astronomical factor is mixed up with the geographical and the meteorological factors so, when fitting the parameters M, A, and B in (3) to a dataset, they will contain information relative to these factors. An example, with all the measurements of two stations ("*Torre Blanca*" and "*Llano de Molina*") and the curve obtained, is given in Figure 8.

The process is valid for all cases studied and the correlation coefficient is always higher than 0.75. The resulting parameters for each station are listed in Table 2.

With (3), once its parameters have been adjusted to a data set, is possible to predict the average of the daily irradiation for a particular site and day. This prediction includes an average of the weather conditions, and the clearly of the atmosphere (turbidity).

Once the data have been adjusted for all seasons, you get a database with the parameters M, A, and B for all measurement points. Maps of global radiation over the entire surface of the Murcia Region are obtained using spatial interpolation techniques. Examples of these maps are represented in the results section of this paper.

4.3.2. Obtaining Diffuse (and Direct) Solar Radiation for Each Station. Diffuse radiation measurements was registered at five meteorological stations ("*Guadalupe,*" "*C del Judio,*" "*Llano de Molina,*" "*La Alberca,*" and "*Torre Blanca*"). The characteristic annual equation (3), fitted to each station data, has been used to computed monthly mean values of diffuse daily irradiation. Using these values, the following third-order polynomial, which relates diffuse (H_d), global (H), and extraterrestrial (H_0) irradiation was obtained following the expression of Liu and Jordan [34], (4). This expression was used for each station where the diffuse irradiation was measured:

$$\frac{H_D}{H} = J_1 - J_2\frac{H_D}{\overline{H}_0} + J_3\left(\frac{H_D}{\overline{H}_0}\right)^2 - J_4\left(\frac{H_D}{\overline{H}_0}\right)^3, \quad (4)$$

where H_D is the annual mean of the daily diffuse irradiation, H is the annual mean of daily irradiation measure in each station, $\overline{H}_0$ is the annual mean of extraterrestrial solar

TABLE 2: Data and results of global irradiation parameter for each measurements stations used in this study.

Ref.	Name	Geographical parameters UTM x (km)	UTM y (km)	Height a.s.l. (m)	Valid Data	Global Irr. parameters M	A	B
AL31	Totana	631.134	4177.380	234	2780	17.351	9.680	3.417
AL51	Librilla	646.202	4196.165	164	2833	16.856	9.830	3.422
CA12	UPCT-La Palma	680.785	4173.450	30	584	14.538	8.431	3.325
CA21	Corvera	665.320	4188.975	225	2780	17.192	9.621	3.433
CA42	Balsapintada	664.924	4179.770	136	2778	16.914	9.656	3.442
CA52	La Aljorra	670.233	4171.939	84	2762	16.674	9.530	3.434
CA72	Roche	683.796	4166.811	63	2793	17.059	9.377	3.465
CA91	El Campillo	655.462	4174.084	174	3133	17.355	9.671	3.417
CI32	Ulea	652.671	4228.482	236	2788	17.598	9.989	3.415
CI52	Calasparra	614.311	4234.953	274	3107	16.001	9.608	3.4302
CR12	Barranda	588.796	4211.407	866	3019	15.954	9.590	3.422
CR42	Moratalla	604.030	4228.626	454	2822	17.266	9.844	3.4083
JU12	C del Judio	637.803	4251.007	394	3126	18.772	10.746	3.421
JU42	Yecla Norte	657.918	4280.624	657	2381	17.477	9.342	3.371
JU52	Yecla-Pinillos	664.558	4270.147	565	2993	15.775	9.744	3.384
JU61	Jumilla	646.291	4259.462	486	3198	14.024	8.482	3.411
LO11	Lorca	621.083	4162,736	323	2536	16.425	9.549	3.415
LO21	Pozohiguera	615.537	4151.777	356	2365	17.392	9.787	3.420
LO31	Aguilas	624.681	4142.445	30	2764	17.59608	9.467	3.440
LO41	La Paca	604.096	4190.668	693	2793	17.632	9.844	3.409
LO61	Puerto Lumbreras	613.917	4160.518	310	3124	16.584	9.344	3.441
ML21	Mula	634.664	4211.679	274	2765	16.674	9.530	3.434
MO12	Torres de Cotillas	648.990	4208.022	157	3042	17.329	9.725	3.324
MO31	Llano de Molina	655.664	4214.906	80	2907	16.481	9.512	3.435
MO41	Abanilla	670.577	4226.616	138	2824	14.734	8.157	3.452
MO51	Fortuna	661.952	4225.502	196	2830	16.263	9.424	3.435
MO61	Ojos	646.290	4221.343	161	2397	17.079	9.534	3.425
MU21	Beniel	675.661	4211.733	27	3182	16.365	9.542	3.449
MU31	Sangonera La Verde	652.374	4196.142	138	3070	15.478	8.784	3.451
MU62	La Alberca	664.029	4201.022	53	3146	16.701	9.529	3.438
TP42	Torre Blanca	685.178	4182.992	31	2607	17.593	9.526	3.459
TP81	Martynez del Puerto	672.353	4186.382	126	643	16.384	9.822	3.415
TP91	Torre Pacheco	677.479	4179.933	53	3650	13.858	8.392	3.349
GUA1	Guadalupe	660.726	4207.774	62	4852	16.501	9.649	3.435
	Mean values					**16.582**	**9.477**	**3.4187**

irradiation, and J_i are the independent parameters to fit the equation for each measurement station.

The fitting of (4) to a dataset has been made by the least-square method, the same method used on global irradiation, and the resulting parameters for each station where was measured diffuse irradiation are listed in Table 3. Two examples, with all the measurements of the stations and the curves obtained (global and diffuse irradiation), are given in Figure 8.

Once we got the global radiation and diffuse radiation, the way to calculate the direct irradiation is by subtracting both arithmeticly ($H_b = H - H_D$). Direct irradiation is not evaluated and neither the maps of direct irradiation were built for this paper because, usually the direct irradiation is not a good parameter to evaluate the viability of photovoltaic and thermal installations.

4.3.3. Obtaining the Mean Daily Temperature. In order to calculate the daily mean temperature at the ground level, is avaible a time serial data over several years of sampling, in each of the weather stations. With this data has been made, a statistical adjustment with a similar method used for the evaluation of global irradiation.

To obtain the most appropriate statistical function to model the temperature, the steps are the following.

Table 3: Parameters for diffuse irradiation for each measurements stations used in this study.

		Diffuse Irr. parameters			
Ref.	Name	J_1	J_2	J_3	J_4
JU12	C del Judio	0.494707	−1.0864082	1.5309554	−0.7406922
MO31	Llano de Molina	0.494707	−1.0864082	1.5309554	−0.7406922
MU62	La Alberca	0.3648796	0.4254933	−2.6507905	2.72899133
TP42	Torre Blanca	0.3272163	1.4254461	−4.4755865	3.6089248
GUA1	Guadalupe	0.9662637	0.664747	−4.0848239	2.2760634
	Mean values	**0.417127806**	**0.291669852**	**−1.876344339**	**1.74839097**

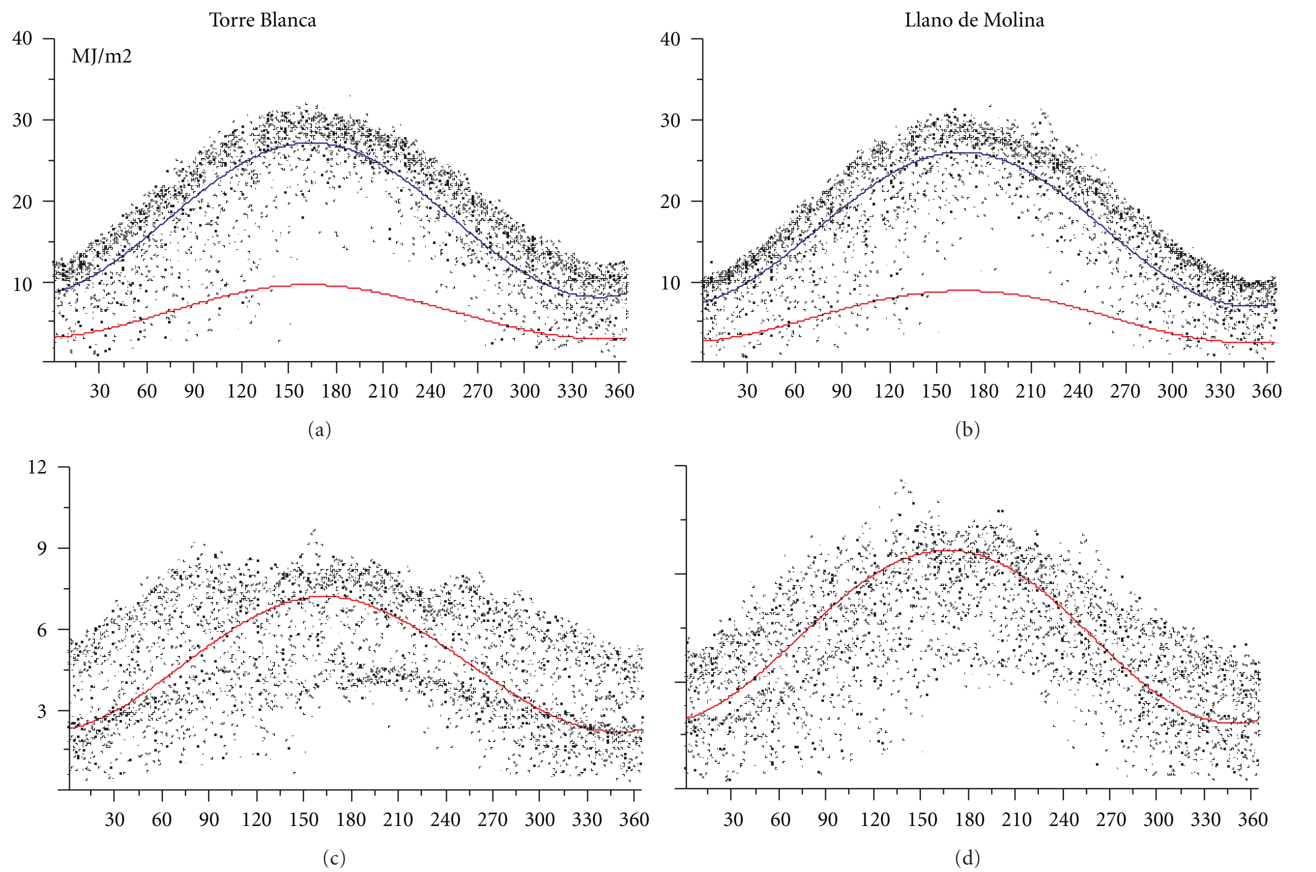

Figure 8: Fitting of (3) for global irradiation (blue line) and (4) for diffuse radiation (red lines) for two sets of measurements of global irradiations (top graphs) and diffuse irradiation (bottom graphs).

Firstly, the mean temperature for each day and for each measuring station were calculated, with these measures, the average over the year available with measure were calculated. An ANOVA (analysis of variance) statistical analysis was done with the IMSL libraries implemented in the program Developer Studio. The average daily temperature over the year and all data available from the measurements stations were used as target for the ANOVA analysis. From this analysis, were found the parameters (variables) more appropriate to model the mean temperature.

According to ANOVA analysis and, coinciding with the literature, the daily mean temperature must include, at least, a fit parameter depending of the location where the calculation is performed. Additionally, the temperature model must have a dependent parameter with the day of the year for latitudes near 40 degrees, just as the global radiation case. And, finally, a parameter of adjustment for the time period when the measurements were taken, to avoid the deviation of the data timing.

With all those considerations, it follows that the function for mean temperature has a shape similar to that used for the

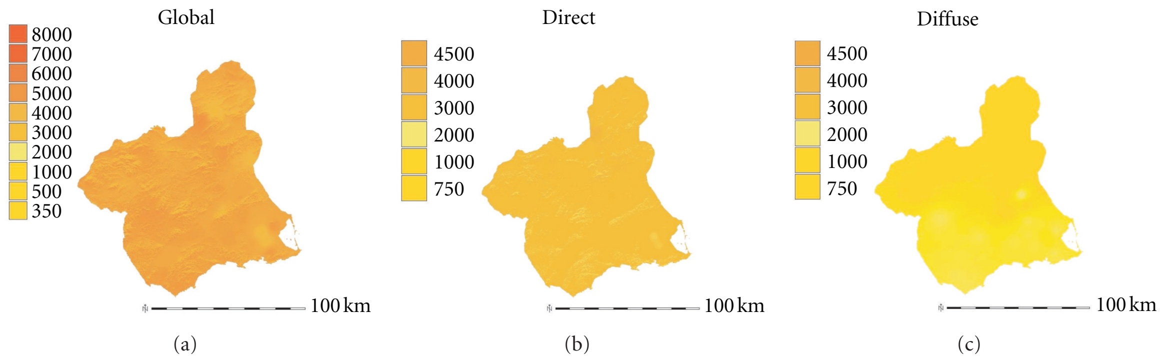

FIGURE 9: Average-annual maps for global, direct, and diffuse irradiation in Murcia.

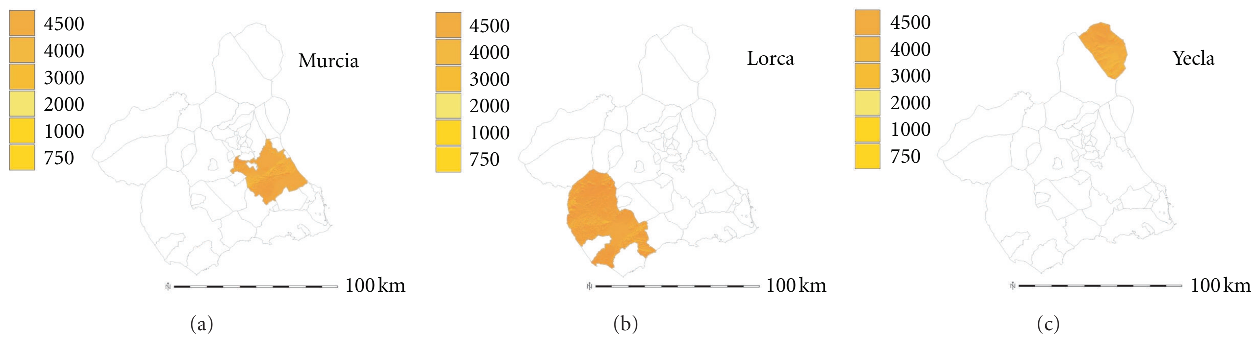

FIGURE 10: Average-annual maps for global irradiation in Murcia for three municipalities.

calculation of mean global daily irradiation but, of course, with different fitting parameters. Equation (5) shows the equation used for daily mean temperature:

$$\overline{T} = T_M + T_A \times \cos\left[\left(\frac{2\pi}{365.25}\right) \times D + T_B\right], \quad (5)$$

where $\overline{T}$ is the mean daily temperature at ground level for each measurements station, D is the Julian day, T_M annual average daily temperature for the location, T_A amplitude of the annual variation for the daily temperature in the location, and T_B is the factor that corrects the gap caused by the calculation start on first of January for the site under study.

In the same way, that global radiation and the fitting parameters obtained from (5) are only valid for each location of measurement stations. One way to check the consistency of the correlation is chosen by comparing the parameters obtained for each station with the average parameters, it was observed that there is a low-level variance for stations located near, on the other hand, the correlation coefficient is usually higher than 0.7, which leads to the conclusion of the correlation is consistent.

With (5), particularized for each measurement station and spatial interpolation techniques of GIS, it was possible to calculate the average temperature at the surface of all the territory covered by the Region of Murcia.

5. Results

5.1. Solar Radiation Maps for Murcia Region. The maps have been built with the use of *r.sun* tool. This tool is based on previous work done by Hofierka [32, 35] and prepared for an open source environment of GRASS GIS [36]. A raster for the terrain was developed with a grid with 250 × 250 metres of spatial steps, and this raster was used for generated the necessary input data for *r.sun* and for generated the intermediate definitive maps of this work. Figure 6 summarizes the methodology follow to obtain the final maps.

The *r.sun* works in two modes. In the mode 1, for the instant time, it calculates a solar incident angle (degrees) and solar irradiance values ($W{\cdot}m^{-2}$). In the mode 2, the daily sum of solar irradiation ($Wh{\cdot}m^{-2}{\cdot}day^{-1}$) and duration of the beam irradiation are computed within a given day. For this work, only the mode 2 has been used. The model requires only a few mandatory input parameters, digital terrain model (elevation, slope, aspect), day number day (for mode 2), and additionally a local solar time (for mode 1). However, several other parameters can be set to fit the specific user needs. These parameters have default values that are used unless they are overridden by user settings as a single value or a name of the raster, as Linke atmospheric turbidity raster or the global irradiation measures. The *r.sun* can take into account the shadowing effect of the terrain.

The *r.sun* model estimates global radiation under clear-sky conditions from the sum of its beam, diffuse, and

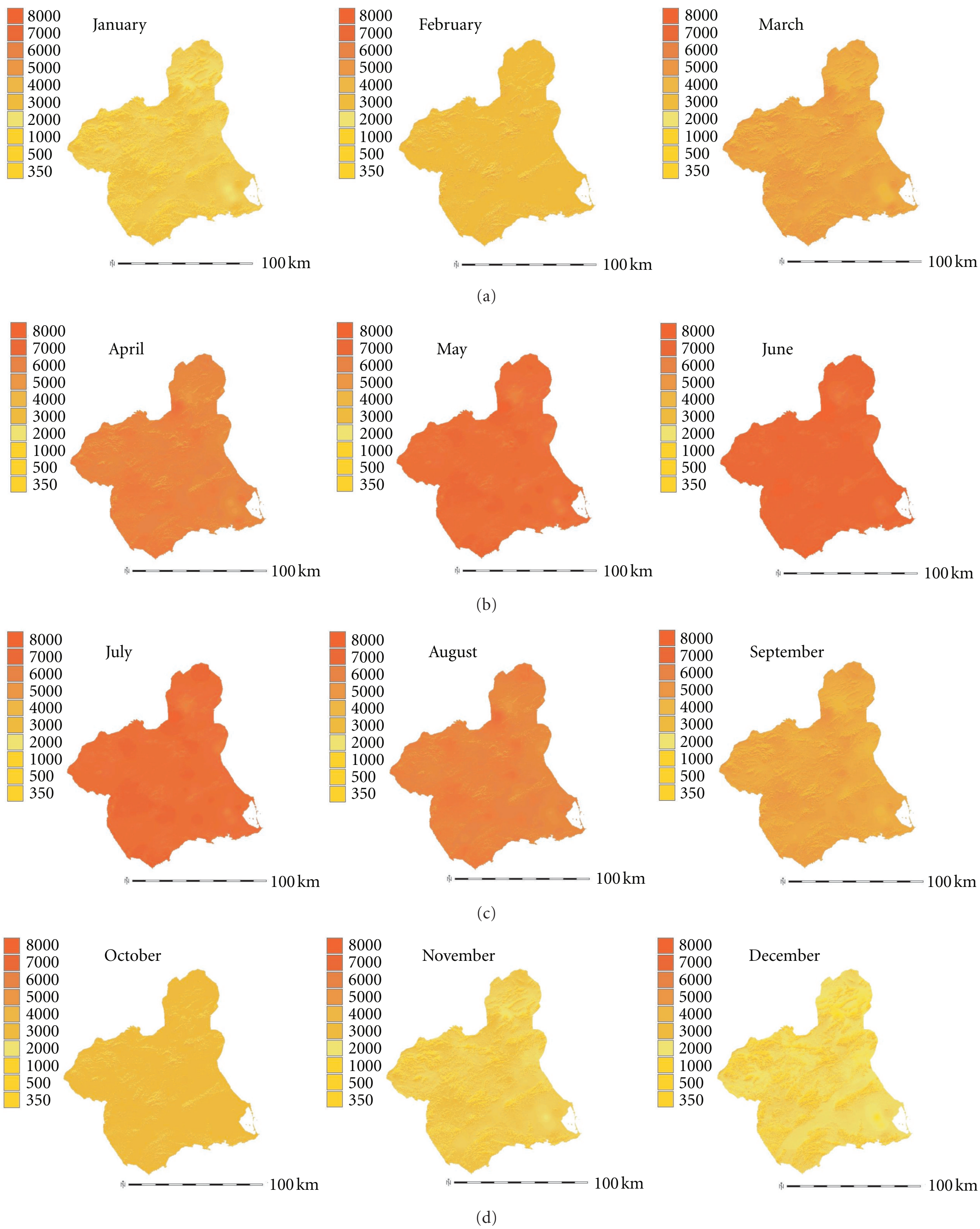

Figure 11: Maps of monthly mean global solar irradiation in $Wh \cdot m^{-2} \cdot day^{-1}$.

reflected components. While the calculation of the beam component is quite straightforward, the main difference between various models is the treatment of the diffuse component. This component depends on climate and regional terrain condition, therefore, it is important to have a largest source of data in and around the area where the irradiation maps have been built.

Overcast radiation can be calculated from the clear-sky values by application of a factor parameterizing the attenuation caused by cloudiness or other factors. For an

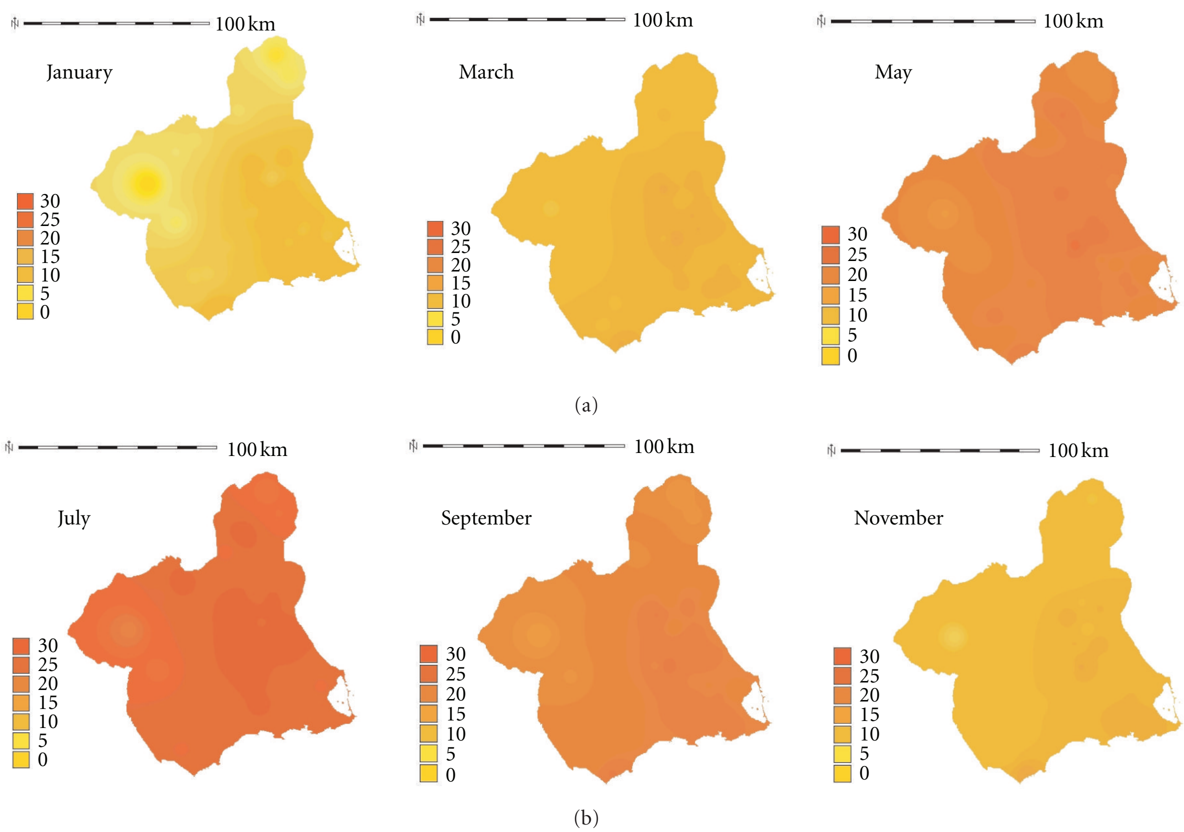

Figure 12: Maps of monthly mean temperature at ground level in (°C).

assessment of global irradiance/irradiation on the horizontal surface for overcast conditions a clear-sky index, K_c was used [37]:

$$K_c = \frac{H}{H_0}. \tag{6}$$

This index is possible calculate with the frequency of sunny-skies, Table 1 and some correlations, or, in the case of this work, K_c can be calculated for ground stations where the global irradiation were measured.

With the previous fitting coefficients for global and diffuse irradiation equations (3) and (4), in each station and for each day of the year, parameters shown in Appendix A were obtained raster layers for all area studied through interpolation of data between stations and also for each day of the year of each station. To obtain the most accurate results a cross-validation procedure was applied separately for each point of datasets of K_c calculated from each data station.

The information is rasterized using the inverse distance method, which estimates the value of each of the cells as a weighted average of the measured values in a set of sampling points located around.

In the last iteration of the process expose in Figure 6, the value of K_c parameter contains all the information of the turbidity of the atmosphere and the overcast of the location, so it is possible to avoid the influence of the Linke factor in *r.sun* to obtain a good agreement with the data.

Figure 9 shows the resulting average-annual maps of the global, direct, and diffuse mean daily irradiation, respectively, in $\mathrm{Wh \cdot m^{-2} \cdot day^{-1}}$. The annual-average maps for show values around 4600 $\mathrm{Wh \cdot m^{-2} \cdot day^{-1}}$ that correspond with 16.6 $\mathrm{MJ \cdot m^{-2}}$ per day for global irradiation, and with a distribution very similar for all region. The global irradiation is obtained with an annual-average value of direct irradiation around 3000 $\mathrm{Wh \cdot m^{-2} \cdot day^{-1}}$ that it is the 65% of the global irradiation.

This map is in fairly good agreement with the European Solar Radiation Atlas data [38, 39].

The monthly maps shown in Figure 11 of Appendix B have been plotted by calculating the mean monthly values from the results obtained for each day of each month.

Figure 11 shows that the spatial differences are not very high for the region. The mean values for global irradiation is around 2400 ($\mathrm{Wh \cdot m^{-2} \cdot day^{-1}}$) for January until 7250 ($\mathrm{Wh \cdot m^{-2} \cdot day^{-1}}$) in July.

In addition, more detailed maps were building for each municipalities of the region, Figure 10 shows three examples. These maps are useful in order to know the behaviour of a solar installation in an specific location.

Another result of the work was to built tables with the mean, maximum and minimum of monthly global irradiation mensual for different location. With the methodology used is also possible to calculate the correction factor to obtain the irradiation in inclination planes. Those tables were

Table 4: Results of parameters for mean temperature for each measurements stations used in this study.

Ref.	Name	Temperature parameters T_M	T_A	T_B
AL31	Totana	16.6787391	8.436983	2.9142238
AL51	Librilla	17.1647676	8.5863201	2.9261178
CA12	UPCT-La Palma	17.4676627	7.8813423	2.8921322
CA21	Corvera	17.1087351	7.946457	2.8805345
CA42	Balsapintada	17.1743524	8.3508872	2.882404
CA52	La Aljorra	17.4707058	7.8344485	2.856199
CA72	Roche	17.2051746	7.7533303	2.8485785
CA91	El Campillo	17.381691	8.3831529	2.9038235
CI32	Ulea	16.8603691	8.5113843	2.9281672
CI52	Calasparra	16.3302953	9.7581206	2.9855845
CR12	Barranda	12.5808302	9.1008209	2.9424775
CR42	Moratalla	15.477021	9.3091126	2.9408925
JU12	C del Judio	15.5617422	9.0119247	2.9573457
JU42	Yecla Norte	13.9980274	9.3290712	2.9527986
JU52	Yecla-Pinillos	14.5329077	9.2507889	2.9768628
JU61	Jumilla	16.695544	9.7005163	2.9695975
LO11	Lorca	16.5691653	8.9163925	2.9121398
LO21	Pozohiguera	16.2682347	8.288988	2.9043525
LO31	Aguilas	18.1338082	7.454142	2.8330426
LO41	La Paca	14.376019	8.9020964	2.9304546
LO61	Puerto Lumbreras	16.5603238	8.9011505	2.9575745
MO12	Torres de Cotillas	17.5487288	8.2362856	2.918409
MO31	Llano de Molina	16.6265034	8.8926416	2.9417652
MO41	Abanilla	16.9638715	8.1939865	2.8993615
MO51	Fortuna	17.5220957	8.2133953	2.9056501
MO61	Ojos	18.2102055	8.2140373	2.9128429
MU21	Beniel	17.1297236	8.5274634	2.9193807
MU31	Sangonera La Verde	18.8742532	8.6920067	2.9342768
MU62	La Alberca	18.0468926	8.8879487	2.9470716
TP42	Torre Blanca	16.5488857	7.9646603	2.8622786
TP81	Martynez del Puerto	16.844607	8.1887913	2.8735671
TP91	Torre Pacheco	17.4197783	7.9798781	2.8972481
GUA1	Guadalupe	18.0769874	8.2316528	2.9059964
	Mean values	**16.709353**	**8.540308418**	**2.915550048**

obtained with the use of *r.sun* tool when the data were fitting and adjustment with the measured data collection.

5.2. Temperature Maps for the Region of Murcia. Similar process was used in order to obtain the mean temperature at ground surface in the region. The filtering process applied to the daily temperature and the information from each station was extended to all region using the inverse distance method, which estimates the value of each of the cells as a weighted average of the measured values in a set of sampling points located around.

The same raster then for irradiation maps was used for the temperature, a grid with 250×250 metres of spatial steps.

Some examples of the resulting maps are show in Figure 12 of Appendix C. The maps present the mean temperature daily for six months of the year in celsius degress. It is possible to appreciate that during the winter the map of January shows a strong minimum in the western plateau, associated with the influence to the high level over the sea of that zone and the influence of the continental weather. This minimum is not appreciate for the mean global irradiation. With these two aspects, it is possible to say that the north west of the region is appropriate to install PV panels and the center and south is more appropriate to install thermal solar collector of high or medium temperature.

6. Conclusions

An elaborated process, valid for middle latitudes (30–50), based on astronomical factor has been used to develop several maps of global, direct and diffuse irradiation in Murcia region. This method has been demonstrated to be useful for a filtering process for a daily solar irradiation data and to make a good treatment of the radiation data by means of an annual characteristic equation for each location. This process was applied to the time series collected from 35 stations and was useful to generate the *Solar Radiation and Mean Temperature Maps of Murcia Region*.

With the results of this study was obtained a useful tool to quantify more accurately the areas in the Region of Murcia where it may be interesting to install solar systems use. This is possible thanks to the combination of the results of global radiation, direct and diffuse on horizontal and inclined plane, and temperature at ground level data.

Although, the mean values obtained present good agreement with the European Atlas. The high density of measuring stations has allowed a detailed spacial analysis of the irradiation and the mean temperature in the studied area.

It has been demonstrated that with the combined use of GIS techniques and an extended data base of radiation it is possible to built useful maps of irradiation and temperature. The tool *r.sun* has been used to develop a serial of maps and mean values of the radiation for different locations and for horizontal plane and for surfaces with several inclinations.

Finally, the results obtained in this work have generated the first edition of Solar Radiation Atlas and temperature in Region of Murcia. This Atlas is designed as a useful tool to help engineers, designers, developers, and so forth, during the selection location process for solar installation.

Appendices

A. Data and Results of Measurements Stations Used in This Study

In this appendix, is presented the geographical parameters of each meteorological station used for this study, coordinates UTM and height at sea level (a.s.l.), and the numbers of valid data.

Table 2 shows the parameters for (3) obtained to calculate the annual mean of daily global irradiation for each measurements station.

Table 3 shows the parameters for (4) obtained to calculate the annual mean of daily diffuse irradiation for the five measurements stations where diffuse irradiation was measured.

Finally, Table 4 shows the parameter for (5) to calculate the mean temperature at ground level for all meteorological stations.

B. Maps of Monthly Mean Global Solar Irradiation

See Figure 11.

C. Maps of Monthly Mean Temperature

See Figure 12.

Nomenclature

A_0: Amplitude of annual oscillation of the daily irradiation
A: Amplitude of the annual variation of daily irradiation in a location, parameters, and Bölcs correlation
B_0: Lag between the first of January and summer solstice
B: Lag caused by the calculation start on first of January for an specific location
D: Julian day
E_0: Eccentricity correction for solar declination, $E_0 = 1 + 0.033\cos((360/365)D)$
EVE: Ente Vasco de la Energía
G_{SC}: Solar constant, 1367 W/m
$\overline{H}_0$: Annual mean daily extraterrestrial irradiation
H_0: Annual mean daily irradiation at sea level
H_b: Annual mean daily direct (bean) irradiation in an specific place
H_D: Diffuse mean daily irradiation in an specific location
H_M: Annual mean of daily irradiation
H: Annual mean of the daily irradiation measure in an specific place
IMIDA: Instituto Murciano de Investigación y Desarrollo Agrario y Alimentario
INM: Instituto Nacional de Meteorología
J_i: Independent parameters to fit the equation of diffuse irradiation in an specific place
M: Annual average daily radiation for an specific location
SoDa: Services for Professionals in Solar Energy and Radiation
UTM: Universal Transverse Mercator coordinates system
WRC: World Radiation Center.

Greeks

δ: Solar declination for each day, $\delta = 23.5\sin((360/365)(D + 284))$
φ: Latitude
ω_S: The angle of the sunrise in sexagesimal grades.

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