Mathematical Interpolation Methods for Spatial Estimation of Global Horizontal Irradiation in Castilla-León, Spain: a case study

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Abstract:

Four spatial interpolation methods (Inverse Distance Weighted, Spline, Kriging and Natural Neighbor) and their different variations are employed to map Global Horizontal Irradiation (GHI) in Castilla-León, Spain. The work has been performed using the software ArcGis, widely used in geostatistical applications, showing the versatility of the system and its applicability to climate data. The measuring network consists of 71 ground meteorological stations that use seven complete years of half-hourly data sets, yielding annual daily averages of GHI. The interpolation results are tested against data from the four Spanish National Meteorological Agency (AEMET) stations available in the region using standard statistical indicators (RMSE, MBE, MAPE and MAE). An additional partial cross validation of the results, which excludes five stations from the measuring network, employs different criteria to verify the results of the interpolation methods applied. This work contributes to the classification of interpolation methods to obtain climatological data across large areas with a low number of irregularly distributed of measurement points and with a low topographic complexity. The Universal Kriging method with quadratic semi-variogram shows the best results taking into account the RMSE and MAE statistical indicators.

Keywords:

Interpolation methods; solar radiation; ground meteorological network; ArcGis.

1. Introduction

Solar radiation is the major available renewable energy source. Solar radiation prediction and forecasting are important for electricity generation and use of alternative energy sources on line. The availability of solar radiation measurements at any given location would give valuable information for the realization of energy projects. This form of resource monitoring is, therefore, critical for system design and assessment, energetic planning, and grid management. A key objective for successful network monitoring is to map relevant parameters and predict their values at unobserved locations, by employing their values at known locations. In the case of solar energy, Global Horizontal Irradiation (GHI) is the most common parameter recorded by meteorological ground stations. Even though their accuracy is restricted, several mathematical methods to obtain values of GHI through the use of different meteorological data, such as temperature, rainfall, and geographical parameters, have been proposed (Ayodele and Ogunjuyigbe, 2015; Chelbi et al., 2015; Dumas et al., 2015; Kim et al., 2014; Mousavi et al., 2015; Sun et al., 2015; Wu et al., 2013). In other hand, satellite based maps a reliable technique widely accepted and several commercial products are available from this technique (Perez et al., 1994). But the ground measurements are essential to test any method to calculate the solar resource. As the number of ground stations is limited, limiting the availability of data, mathematical interpolation methods can provide suitable results, without the need to establish additional meteorological parameters.

In this work, four main interpolation methods and 29 variations were used to map annual daily average values of GHI (MJ m^{-2} day^{-1}) from a network of 71 ground stations in Castilla-León, Spain. The four AEMET (National Meteorological Agency) facilities in the region constitute the control system. Standard statistical indicators are used to classify the interpolation methods. The main novelty of the paper is the classification of classical interpolation mathematical methods for solar radiation data over large areas with few measuring points. The work has been performed using the ArcGis Software, which is widely used in geostatistical applications, showing the versatility of the system and its applicability to climate data.

The work is organised as follows: The region under study and its climatic characteristic are described in Section 2; both ground meteorological networks, SIAR and AEMET, used for the application of the interpolation methods and their validation are described in the Section 3. In Section 4 a wide review of the main interpolation methods traditionally used for climatic data is presented. The obtained results from the application of the interpolation methods on the basis of the classical statistical indicators are presented and discussed in Section 5. Finally, the main conclusions and contributions of the paper are detailed in Section 6.

2. The region under study

Castilla-León is a Spanish region located in the northern half of the central Meseta, an extensive plateau with a very low population density (27 habitants/km^2) that occupies a surface area of 94226 km^2. Surrounded by mountain ranges, with heights in the range between 700 and 1000 m above sea level. The continental Mediterranean climate of Castilla-León has long, cold winters with average ambient temperatures between 4ºC and 7ºC in January and short, dry and hot summers, with ambient temperatures between 19ºC and 22ºC. Scant rainfall is accentuated in lower areas, as the higher mountainous areas act as natural barriers, interrupting cloud formation and causing uneven patterns of precipitation.

Three different climatic areas may be identified: a) to the north, at the highest part of the Cantabrian Mountains, an Atlantic climate, with mild winters and summers. At lower elevations, typical Atlantic climates prevail with very cold winters; b) the central area of the plateau is dominated by a Continental Mediterranean climate with hot summers and severe winters, except to the east of the province of Zamora, where the climate is much drier. c) A typical mountainous Mediterranean climate prevails in the highly elevated areas of the north-east, east and south, with hot summers, cold winters and low rainfall. Figure 1 shows the geographical location of Castilla-León.

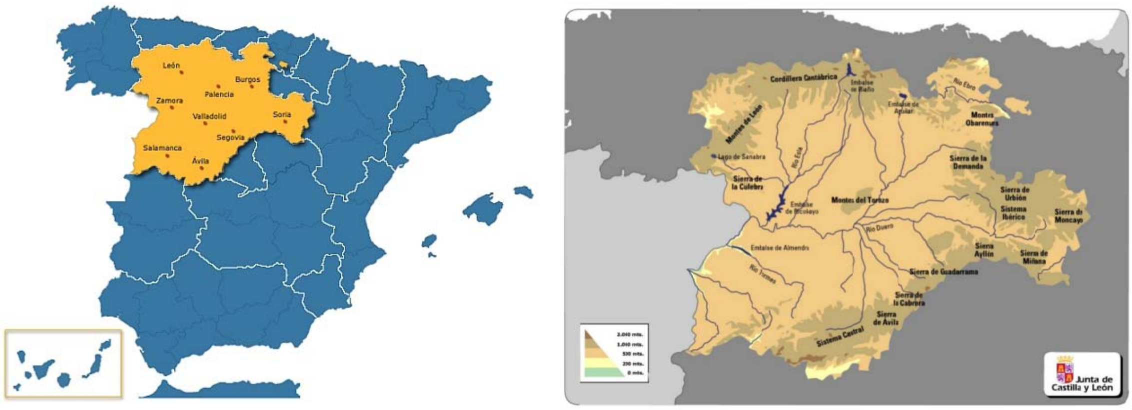

Figure 1. a) Location of Castilla-León, Spain; b) River Duero flowing across the region from East to West (Source: http://navalmanzano.com/ ; http://mapasinteractivos.didactalia.net/

Among the geophysical and climatic features described above, the height above sea level of Castilla-León, above that of its surrounding regions, may be the most influential factor in the solar radiation that it receives. The geographical coordinates (40º05' longitude and 43º14' latitude) mean that the diurnal duration between winter (slightly less than nine hours) and summer (over 15 hours) is markedly different, a fact that implies much higher levels of irradiance in summer than in winter.

3. Experimental Section

3.1. SIAR network

SIAR (*Sistema de Información Agroalimentaria para el Regadío*, Agricultural Information System for Irrigation) (Ministerio de Agricultura) is a ground meteorological network jointly operated by the Spanish Government and the Autonomous Communities. In

Castilla-León, the SIAR System has 53 ground stations, which collect data on GHI, temperature, rainfall, humidity, wind speed and wind direction. The locations of each station comply with the directives of both the World Meteorological Organization (WMO) (World Meteorological Organization, 2012) and AEMET (Agencia Estatal de Meteorología). A Skye SP1110 pyranometer (spectral range 350-1100 nm, uncertainty ±5%), calibrated in accordance with ISO 9847, is used to measure GHI with a sampling rate of 10 seconds. Half-hourly data are logged by a SR1000 Campbell datalogger. A strict filtering procedure has been applied to the available data and the number of ground stations supplying data for the study has been limited to 44 (see Figure 2). This meteorological network has been amply used to test different methodologies to obtain solar irradiation maps by using support vector machines (Antonanzas-Torres et al., 2015; Antonanzas et al., 2015), satellite data (Antonanzas-Torres et al., 2013a) or parametric (Antonanzas-Torres et al., 2013b) and predictive models (Urraca et al., 2016).

3.2.The boundary area

The SIAR network has few ground stations along the borders of the Region, so a set of ground station in the neighboring regions were used to mitigate abrupt responses in the interpolation method. The search to find ground stations in the boundaries with similar technical characteristics and data over the same time period was, therefore, extended to the regions of Galicia, Asturias, Cantabria, País Vasco, La Rioja, Aragón, Castilla La Mancha, Madrid, Extremadura and Portugal.

3.3. The control network: AEMET ground stations

The AEMET stations located in Castilla-León were reserved as the validation sites, and were not used for the interpolation methods. Only four stations in the AEMET network record GHI data in Castilla-León. Kipp&Zonen CM11 or CM21 pyranometers (spectral range 305-2800 nm, uncertainty ±2%) are used to record 10 seconds GHI data. Cumulative hourly GHI values were calculated using the integration trapezoidal rules over the 10 seconds values. A partial cross-validation of the results in accordance with different criteria was also performed using five additional controls; each consisting of five stations (approximately 10% of the total SIAR network) in the interpolation network.

3.4. Data processing

Data sets from 2007 to 2013 (seven complete years) were compiled for the study. Data available from the SIAR meteorological network were stored on a database and validated in accordance with UNE 500540-2004 (Guidance for the validation of weather data from station networks). Moreover, the data were checked against the WMO criteria as a safeguard against faulty data. Further quality criteria secured that only the stations that had logged at least five complete years, with no less than 335 data sets per year, were considered for the study. In summary, sixty-seven ground stations were used for this study: 44 of them from Castilla-León and 27 located outside the Region but close to its borders. Figure 2 shows the distribution of all ground stations that gave 110080 daily GHI values used in the study. Cumulative daily GHI values were calculated using the integration trapezoidal rules over the half-hourly values of the database.

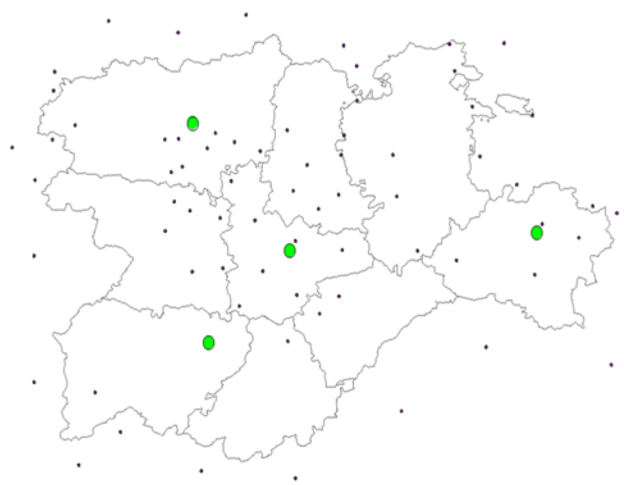

Figure 2: Complete meteorological network used in this study. Small dots represent the interpolation network stations and large dots represent the four AEMET validation sites

Different interpolation methods implemented in ArcGis-10 Software were applied to the data: Inverse Distance Weighted (IDW), Natural Neighbor, Spline and Kriging. 29 variants of these methods were used, changing different parameters as the number of interpolation points, weight or power. The four conventional statistical indicators in use, RMSE, MBE, MAE and MAPE (%), are defined as follows:

$$RMSE = \sqrt{\frac{\sum(v_r - v_i)^2}{N}} \qquad RMSE\ \% = \frac{RMSE \times 100}{Average\ (v_r)} \qquad \text{(Eq. 1)}$$

$$MBE = \frac{1}{N}\sum\ (v_r - v_i) \qquad MBE\ \% = \frac{MBE \times 100}{Average\ (v_r)} \qquad \text{(Eq. 2)}$$

$$MAE = \frac{1}{N}\sum|v_r - v_i| \qquad MAE\ \% = \frac{MAE \times 100}{Average\ (v_r)} \qquad \text{(Eq. 3.)}$$

$$MAPE = \frac{1}{N}\sum\left|\frac{v_r - v_i}{v_r}\right| \times 100 \qquad \text{(Eq. 4)}$$

where, v_r is the experimental value and v_i is the calculated one. These statistical indicators are representative values of the quality of the interpolation method used to fit the data

4. Interpolation methods for climatic and meteorological data

Interpolation methods have traditionally been applied to geospatial data, based on Tobler's first law of geography: "*Everything is related to everything else, but near things are more related than distant things*" (Tobler, 1979). Franke (Franke, 1982), and Lam (Lam, 1983) reviewed and classified various interpolation techniques. A complete report about interpolation techniques for Solar Radiation data was published by IEA (International Energy Agency) (Zelenka et al., 1992). The main novelty of the present work is the use of ArcGis 10 Software that implements the interpolation methods and maps the results. A viewable rectangular (raster map) pixel grid of the working area was built by applying the mathematical interpolation methods to the interpolation network. Several methods were implemented in the software. The use of ArcGIS allows the modification of the different parameters of the interpolation methods easily and fast to perform a complete study of the available data. The results can be presented in the form of maps onto the studied area. The main characteristics of these methods are summarized below.

4.1 Inverse Distance Weighting (IDW)

The simplest spatial interpolation method is the IDW (Inverse Distance Weighting) method, consisting of weighting the inverse of the distance between two points in the sample. The influence of the proximity between data can be defined in a deterministic or an analytical way (Gutierrez-Corea et al., 2014). This method has been used successfully to obtain climatic parameters, (Apaydin et al., 2004; Güler, 2014; Wu et al., 2013). Antonanzas et al (Antonanzas et al., 2015) indicated that IDW is a suitable method to estimate GHI in areas where a low number of solar stations is available.

The fundamental parameter of the method is the power, assigned to calculate the influence of the known values (interpolation network) to the calculated values depending on the distance between them. Power is a real positive number that controls the influence of the nearest points obtaining softer surfaces when the power is fixed to 2. An optimization engine is available in ArcGis to fix this parameter. All interpolated points must tie within the range of the data and if peaks and troughs are not specifically sampled, they cannot be inferred.(Watson and Philip, 1985)..

4.2. Kriging method

Kriging is the other standard interpolation procedure. The interpolated values are modeled by a Gaussian process governed by a previous co-variance estimation method. This method uses a variogram model for data collection, calculating the weights given to each point used in the valuation of the references. This interpolation technique is based on the premise that spatial variation continues in the same tendency. Different weighting calculation procedures may be deduced, depending on the stochastic properties of the random field and the various degrees of assumed stationarity. Universal Kriging (UK) assumes a structural component in the series of values, which implies a local variable trend. In Ordinary Kriging (OK), local averages are not necessarily close to the population mean, so that neighboring points are hardly used for estimation. The available variogram models are linear and quadratic for UK and circular, spherical, exponential, Gaussian and linear for OK.

The Kriging method can provide suitable results for GHI values in homogenous places, with similar climatic parameters. But height, orientation and possible shadows caused by the specific topographical variations in complex topographic areas could negatively influence the results, making them less reliable. Different Kriging methods have been used in this way by Alsamamra et al. (Alsamamra et al., 2009) introducing other external variables to include additional information to improve the results, or to complete unknown values in a database of continuous data (Goovaerts, 2000; Jeffrey et al., 2001; Kambezidis et al., 2016).The Kriging method reduces significantly the errors when more points are used in the interpolation network (Antonanzas et al., 2015)

4.3. Natural Neighbor

Values that are closer to the search point are used as input data for the natural neighbor interpolation. The weighting of each point is based on proportional areas. This method is known as Sibson's interpolation (Sibson, 1981). The natural neighbors of a point are those associated with adjacent Thiessen polygons. A Voronoi's diagram with all of the interpolation data is built around the search point as well as the new polygons. The overlap between both areas is assumed as the weighting.

4.4. Splines

A spline is a piecewise differential function defined through low-degree polynomial functions (to avoid fluctuations caused by higher polynomial degrees), which generates a surface containing all the input data. Intervals are needed to avoid abrupt changes in large surfaces. A complete mathematical formalism was developed by Wahba et al. (Wahba and Wendelberger, 1980) modifying Sasaki's approach (Sasaki et al., 1960)

The values are estimated using a mathematical function that minimizes the general curvature of the surface for obtaining a smooth surface that contains all the input data. Two additional parameters are needed to control the output: the weighting and the number of points. The weight reflects the contribution to the results of the third derivatives of the function. The output surface is smoother at higher weighting values. The number of points used for the interpolation has some influence on the shape of the surface, but increases the computation time.

5. Results and Discussion

A preliminary analysis of the results using 46 stations of the SIAR network was carried out to establish the distribution of the irradiation across the studied area. Average daily GHI (MJ $m^{-2}day^{-1}$) was calculated for the 46 stations of the SIAR network chosen for the study using the available data of the 7-year period. Values of maximum, minimum and average daily GHI were calculated for all stations and years. Significant differences between the stations were found, as shown in Figure 3. Comparisons between the seven year GHI average and the GHI average for a single year average reflected important differences, as can be seen in Figure 3: 2009 was above average and 2013 below average for the complete network. As an initial result, the number and the particular characteristic of the years considered for the study have a very significant influence on the results. Therefore, very long data series are necessary to obtain conclusive results in these kinds of studies.

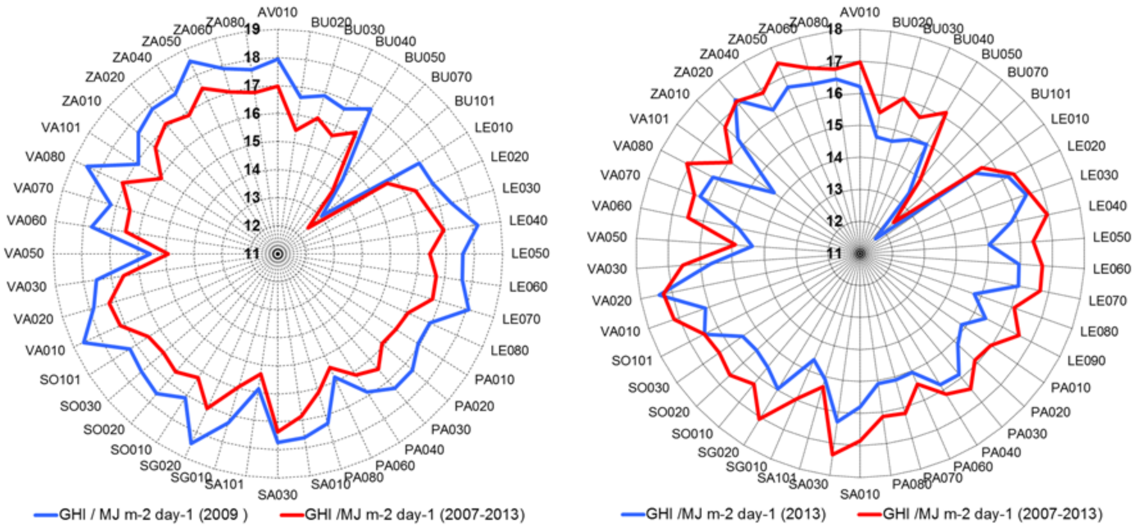

Figure 3: Comparison of daily annual average of GHI (MJ m^{-2} day^{-1}) calculated using 1-year data (2009 or 2013) and 7-year data (2007-2013)

Maps of the annual daily GHI average (MJm^{-2} day^{-1}) in Castilla-León were calculated using the following interpolation methods and their different variations: IDW, Natural Neighbor, Kriging and Splines. A partial-cross validation was performed: five controls were established using the 5 stations in the control system (10% of the total) and 66 stations in the interpolation network. In each control (1 - 5), interpolated values were compared to those measured at the validation sites using the previously defined standard statistical indicators. Different criteria were used to select the stations for each control: longitude and latitude of the stations, proximity between them, and proximity to the border area, as well as proximity between the validation sites and the interpolation network stations. Figure 4 shows the distribution of the stations used in each control in the Region. Definitive control was performed using the AEMET stations in the Region (Control 6).

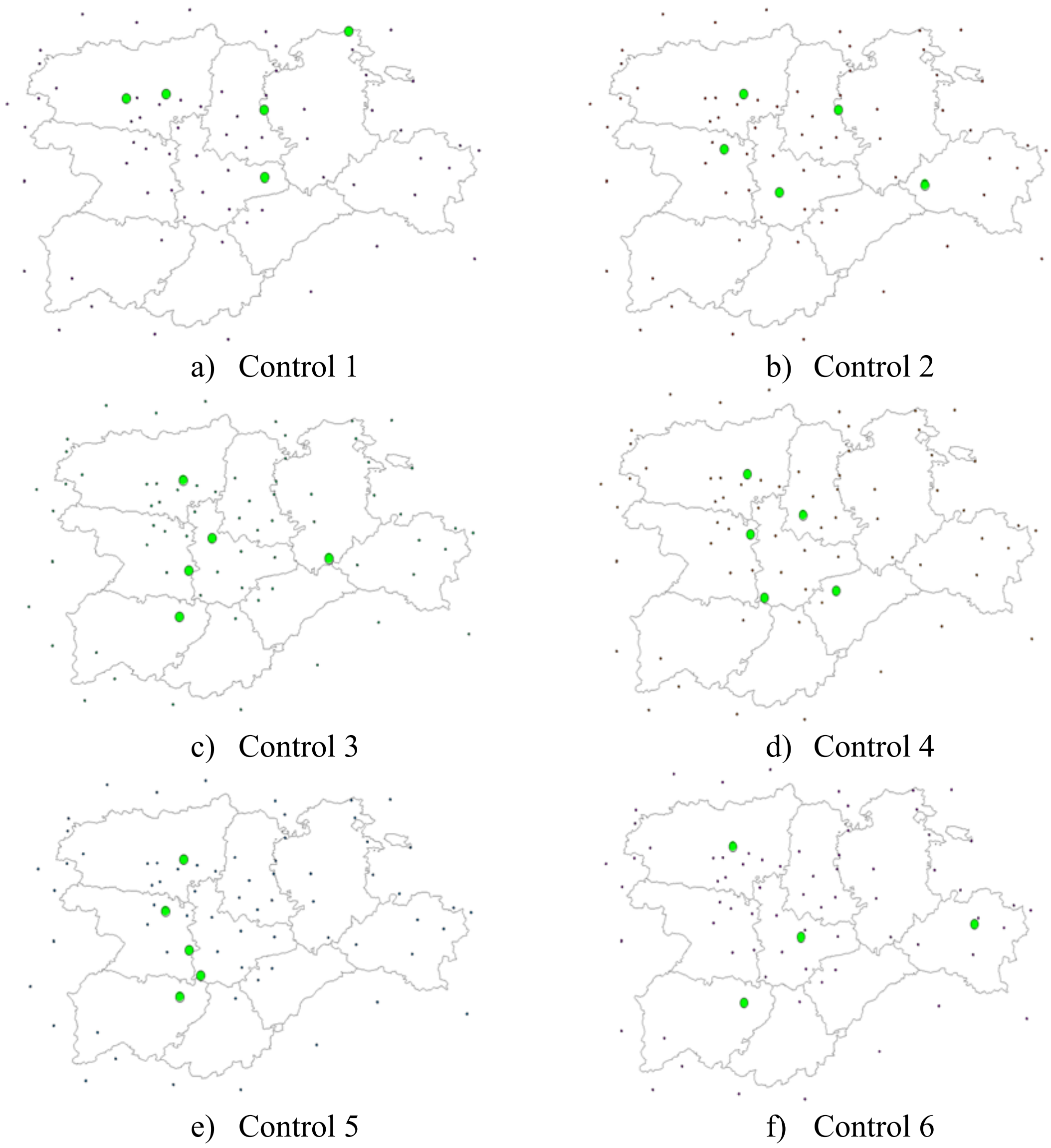

Figure 4: Distribution of the stations chosen for each control system following different criteria : a) Control 1: Stations located in the North of the Region under study including a station at the border; b) Control 2: Stations at some distance from each other that cover the most extensive area and include at least one station per province; c) Control 3: Stations at some distance from each other which cover the largest possible area and include an isolated station; d) Control 4: Stations centered in the area under study; e) Control 5: Stations on a similar longitude; f) Control 6: Definitive control system using the AEMET stations in the Region.

All the methods yielded RMSE values below 6%; the use of different control systems (controls 1 to 5) added no significant differences. Using stations belonging to the SIAR network as the control stations, the OK method with 35 stations and quadratic semivariogram showed the highest RMSE value (5.7%). The UK- method with 35 stations and the quadratic semivariogram showed the lowest MAE value. In Table 1, the results of the interpolation methods and variations, using the AEMET control system stations, are shown. The previously defined statistical parameters -RMSE (%), MBE (%), MAE(%) and MAPE(%)- are included. All these methods presented RMSE (%) values lower than 4%.

Table 1: Standard Statistical indicators (%) of the results of the different spatial interpolation methods applied to the SIAR network in Castilla-León. Control implemented by the four AEMET stations located in the region

CONTROL 6: AEMET STATIONS								
Method	Variation			RMSE (%)	MBE (%)	MAE (%)	MAPE (%)
KRIGING 12 STATIONS	OK	Spherical		2.651	-0.585	2.458	2.500
		Circular		2.647	-0.583	2.454	2.445
		Exponential		2.625	-0.581	2.431	2.422
		Gaussian		3.856	-2.196	3.193	3.213
		Linear		2.641	-0.580	2.448	2.438
	UK	Linear		3.362	1.694	2.641	2.650
		Quadratic		2.377	0.924	2.129	2.141
KRIGING 35 STATIONS	OK	Spherical		2.625	-0.581	2.431	2.422
		Circular		2.688	-0.653	2.510	2.501
		Exponential		2.620	-0.531	2.439	2.430
		Gaussian		5.702	-2.740	4.574	4.622
		Linear		2.596	-0.202	2.343	2.329
	UK	Linear		5.103	3.191	3.670	3.698
		Quadratic		1.434	-0.082	1.260	1.252
SPLINE 12 STATIONS	REGULARIZED	WEIGHT	0.1	3.306	-1.402	2.979	2.986
			0.01	3.191	-1.218	2.943	2.947
			0.001	3.080	-1.095	2.868	2.869
	TENSION	WEIGHT	1	3.000	-1.015	2.804	2.804
			5	3.007	-0.984	2.824	2.824
			10	3.006	-0.959	2.830	2.829
SPLINE 35 STATIONS	REGULARIZED	WEIGHT	0.1	3.410	-1.340	3.124	3.133
			0.01	3.342	-1.232	3.105	3.112
			0.001	3.206	-1.112	3.006	3.010
	TENSION	WEIGHT	1	3.070	-1.0190	2.887	2.890
			5	3.070	-0.995	2.894	2.900
			10	3.066	-0.977	2.895	2.900
IDW		12 STATIONS		2.377	-1.259	2.018	2.006
		35 STATIONS		2.231	-1.060	1.692	1.681
NATURAL NEIGHBOR		12 STATIONS		2.691	-0.081	2.417	2.401

The interpolation methods underestimate GHI, as show the negative values of MBE. “The interpolation method that gave the lowest RMSE value (1.4 %), significantly lower than the other analyzed methods, was UK-35 stations, quadratic semi variogram. The other statistical indicators calculated, MBE, MAE and MAPE, show also the lowest values for the same case. This method was considered the best for this Region and data series. Figure 5 shows the annual daily average of GHI maps in Castilla-León calculated by different interpolation methods. Figure 5-a shows the results using the UK interpolation method and the linear semivariogram (12 stations) and Figure 5-b the UK-linear method (35 stations), which influences the grid resolution. Similar results are shown in Figures 5-c and 5-d for the IDW interpolation method and in Figures 5-e and 5-f for the Regularized Spline (RS). Numerical indicators of these figures are shown in Table 1. As can be seen, the resolution of the grid (number of interpolation points) is not related to the performance of the method: UK and RS yielded the most promising results using a 12-point interpolation rather than a 35-point interpolation, in opposition to the IDW method, which presented better results using a 35-point interpolation.

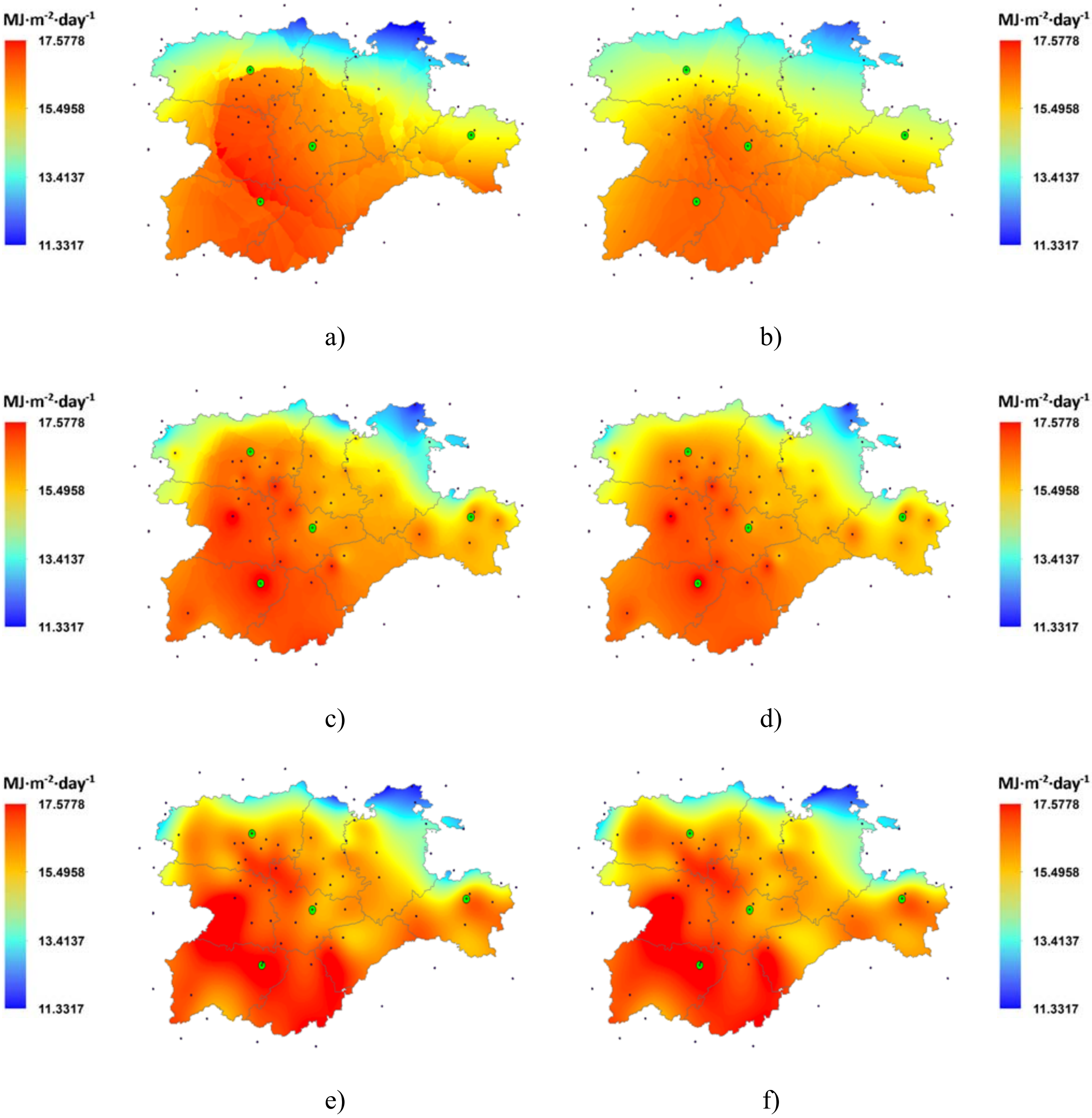

Figure 5: Maps of daily average of GHI (MJ m^{-2} day^{-1}) obtained through different interpolation methods and variations of them; a) UK-linear-12; b) UK linear-35; c) IDW-12; d) IDW-35; e) Regularized Spline, 12 points, weight 0.01; f) Regularized Spline, 35 points, weight 0.01

6. Conclusions

Conventional interpolation methods for climatic and meteorological data have been reviewed and applied to build global horizontal irradiation maps in Castilla-León, Spain. Strict quality controls have been applied to the available data supplied by SIAR, the ground meteorological network used for this work. The SIAR network in the area under study has been complemented by similar ground stations in the boundary area to avoid abrupt responses of the interpolation methods. The interpolation network was, therefore, consisted of 71 stations: 44 in Castilla-León and 27 in the boundary area. Seven complete years of half-hourly GHI data have been used to calculate daily GHI and to obtain annual averages. Significant differences have been found in the seven-year data series, a result that highlights the decisive nature of the temporal series in the results.

An important difference in the annual daily average value of GHI has been observed across the Region from east to west, with a maximum difference of 12.7% across 250 km. This difference had a significant impact on the electrical production at PV facilities, which can be estimated at 7200 €/year for a typical 100 kW facility under current Spanish Legislation. GHI values were estimated in the range 14-18 MJm^{-2} day^{-1}, equivalent to 4 kWh/day or 1460 kWh/year per installed kW. This variation could be explained by the geographical characteristic of the Region with an extensive plain to the west that is not conducive to the accumulation of cloud cover.

The work has been performed using the ArcGis-10 Software, widely used in geoestatistical applications. This system allows an easy implementation of the different interpolation methods, modifying the parameters necessary to perform a complete study of the available data.

On the basis of the individual goodness of each interpolation method in this investigation, the application of Ordinary Kriging with Gaussian semi-variograms to the area under study has been rejected. This method always obtained the highest deviation from the experimental results (regardless of the controls in use). The number of interpolation points (12 or 35) had no significant influence on the results. The best interpolation method for the area under study was UK-35 points and quadratic semi-variogram taking the RMSE and MAE results into account.

A more homogeneous distribution of the stations in the interpolation network would be advisable, to improve the results of this study. As Figure 2 shows, there is an accumulation of ground stations in the center of the region but large empty areas around the boundaries. In this sense, this work shows that the interpolation methods are a suitable procedure to obtain climatological data across large areas with a low number of irregularly distributed of measurement points and with a low topographic complexity.

7. Acknowledgments

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