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On the use of the digital elevation model to estimate the solar radiation in areas of complex topography

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The development of solar energy as a power source in the next few years requires reliable estimation of available solar energy resources. At local scales, topography is the most important factor in determining the distribution of solar radiation at the surface. Interpolation techniques are usually employed to estimate solar radiation where stations are not available, but their usefulness is limited where topography is an important source of variability. The use of satellite data and more recently of models based on techniques GIS, have contributed to solve this difficulty. In this work the usefulness of a digital elevation model (DEM) in providing topographic information for the estimation of solar radiation in areas of complex topography is analysed. Daily global radiation values were generated using the Solar Analyst software, which uses topographic information to generate radiation data. The generated data were compared with the experimental data obtained from 14 radiometric stations located within the Sierra Nevada Natural Park (southern Spain), an area of complex topography. Results show the usefulness of the topographic information derived from a DEM to estimate the solar radiation in areas of complex topography. Nevertheless, results depend on the DEM resolution and it is important that other factors, such as the albedo, should also be taken into account to obtain better estimates.

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1. Introduction

Solar radiation plays a major role in the energy exchange process between the atmosphere and the Earth's surface (Jacobson 1999; Oliphant et al. 2003). As a consequence, the spatial and temporal heterogeneity of incoming solar energy determines the dynamics of many landscape processes, e.g. air and soil temperature and moisture, snow melting, photosynthesis and evapotranspiration, all of which can have a direct impact on human society. Knowledge of the spatial distribution of solar radiation is therefore vital in climatology, ecology, building design, land management and environmental science in general (Dubayah & Rich 1996; Hofierka & Suri 2002). In zones of complex topography, variability in elevation, surface orientation (slope and aspect), and shadows cast by topographic features create strong local gradients of insolation. This leads to high spatial and temporal heterogeneity in local energy and water balance, which determines microenvironmental factors such as air and soil temperature variability, evapotranspiration, snow-melt patterns, soil moisture, and the amount of light available for photosynthesis. These zones of complex topography therefore form very interesting bioclimatic regions, many of which are remote and inaccessible, and many of them are in national parks. The importance of determining the spatial distribution of solar radiation in these types of region is twofold: (1) the amount of radiation received at the Earth's surface is a major forcing function of forest ecology and, consequently, the spatial and temporal distribution of surface radiation exerts a fundamental control on forest patterns (McKenney et al. 1999); and (2) the development of solar energy applications (thermal and photovoltaic) will have major implications in the future. This means that a reliable estimation of the available solar energy resources is important, especially in remote areas where measured data are not available.

Different interpolation techniques have been proposed in the last decades to derive spatial databases from measurements of meteorological and climatological stations, such as spline functions (Sampson & Guttorp 1992; Xia et al. 2000; Jeffrey et al. 2001), weighted average procedures or kriging (Zelenka et al. 1992; Hulme et al. 1995). Such techniques can provide reasonable estimates in homogeneous terrain with similar climatological properties, but reliability decreases when the complexity of the topography increases or in coastal areas. In summary, the simple interpolation and extrapolation of point-specific measurements of solar radiation to all areas is generally not appropriate because most of the locations are affected by strong local variations.

Spatially continuous irradiance values can be derived directly from meteorological geostationary satellites. Processing satellite data provides less accurate values (compared with ground measurements), but has the advantage of having much greater spatial coverage. For instance, the Meteosat Second Generation has a temporal resolution of 15 minutes and a spatial resolution of 2.5 km at the sub-satellite point. In spite of the great improvement compared to the previous Meteosat generation, many applications still need a better spatial-temporal resolution and the usefulness of the solar radiation estimates for areas of complex topography is limited. For instance, in the Sierra Nevada Natural Park in an area of $10 \times 5\,km^2$, elevations can vary by 1000 m and a wide range of aspects can be found. As a consequence, very different solar irradiance values can be obtained in a single pixel. The solar irradiance estimated from the satellite image for a pixel is an average value, but this value does not provide information about intra-pixel variability. Nevertheless, several workers have shown the usefulness of the satellite estimates in providing additional information for interpolation techniques of solar radiation estimation in mountainous regions (Agostino & Zelenka 1992; Beyer et al. 1997).

In the last decade, a new technique for estimating solar radiation in areas of complex topography has been proposed. This technique uses information from a DEM (e.g. slope and aspect) integrated within a geographical information system (GIS) to provide rapid, cost-efficient and accurate estimations of solar radiation over large areas. Currently, there are several software packages that offer different methodologies, such as ArcInfo GIS (SolarFlux: Dubayah & Rich 1995; Hetrick et al. 1993; Solar Analyst: Fu & Rich 2000), SRAD (Wilson & Gallant 2000), IDRISI (Solei: Miklánek 1993) or GRASS (r.sun: Hofierka & Suri 2002).

In the present work the reliability of this type of technique for estimating solar radiation in areas of complex topography is evaluated using experimental data. The ArcInfo Solar Analyst software package is used to estimate the daily global radiation data in the area of the Sierra Nevada Natural Park (southern Spain). Solar radiation estimates are tested against measured values collected by a set of 14 radiometric stations, with the aim of measuring the level of reliability of these model estimates and detecting the sources of error and ways for improvement.

In Section 2, a brief review of the Solar Analyst model is carried out, and Section 3 deals with the study area and the experimental data. Section 4 presents the results and, finally, in Section 5 some concluding remarks are provided.

2. Models based on the DEM and the Solar Analyst model

The DEM provides an opportunity to take into account the important role that the topographic characteristics (elevation, aspect, slope and skyview) play in the spatial and temporal distribution of solar radiation in complex topography.

The influence of the topography can be computed, using the DEM, through a geometric procedure whose accuracy depends on the DEM resolution (Dubayah & Rich 1995; Rich et al. 1995). For each point, the DEM provides the artificial horizon and relative position of the Sun (Duguay 1993). Given the relative position of the Sun at each time and for every point of the area, the direct and diffuse solar irradiance can also be estimated, thereby determining whether the global radiation is made up of direct and diffuse radiation (when the Sun is unobstructed) or comprises diffuse radiation only (when the Sun is obstructed). Daily solar global irradiation is then computed by integrating the instantaneous global irradiance values.

There are two types of models for estimating solar radiation at the surface: point-specific models and area-based models. Point-specific models compute insolation for a location based upon the geometry of the surface, the visible sky from the specific point and the actual position of the Sun. The local effect of topography is incorporated into the model by empirical or visual estimation. Point-specific models can be highly accurate for a given location (Fu & Rich 2000), but not for an entire landscape – it is simply not possible to build a specific model for each location over a landscape. Note that every point presents different relative positions to the Sun's orbit and different geometries report different artificial horizons. In contrast, area-based models compute insolation for a geographical area, computing surface orientation and shadow effects from a digital elevation model (Dubayah & Rich 1995, 1996; Rich et al. 1995; Kumar et al. 1997). As a consequence, whereas point-specific models can be highly accurate for a specific location, area-based models can calculate insolation for every location over a landscape.

Solar Analyst draws on the strengths of both point-specific and area-based models. In particular, it generates an upward-looking hemispherical 'viewshed', for every location of the DEM. A viewshed is the angular distribution of sky obstruction and it is computed for each cell of the DEM. This is similar to the view provided by upward-looking hemispherical

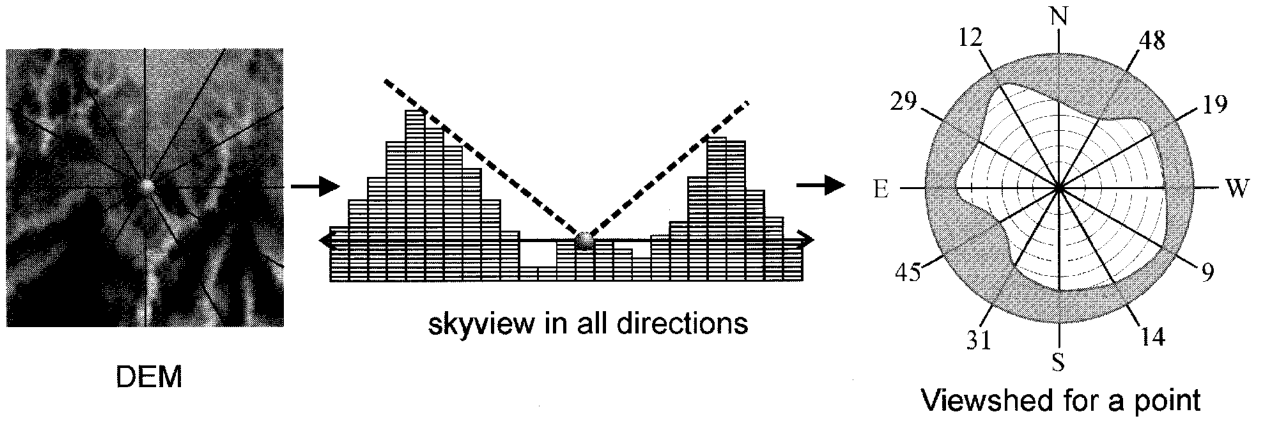

Figure 1. *Schematic process to obtain the solar radiation value at a particular site. Based on a DEM, the sky view is obtained by determining the maximum angle of sky obstruction in each direction. The viewshed is then computed at every site using a hemispheric projection. (Based on Fu & Rich 2000.)*

(fisheye) photographs. The viewshed is constructed by searching in a specified set of directions around a location of interest and determining the maximum angle of sky obstruction in each direction. For other unsearched directions, horizon angles are calculated using interpolation. The horizon angles are then converted into a hemispherical coordinate system (Fu & Rich 2000). To compute the viewshed from a particular location, the artificial horizon is analysed based on the surrounding topography. Furthermore, the DEM must cover an area greater than the area under study. The scheme in Figure 1 shows this process. The hemispherical viewshed is used to compute the insolation for each location and to produce an accurate insolation map. Solar Analyst can calculate insolation integrated for any period. It can account for site latitude and elevation, surface orientation, shadows cast by surrounding topography, daily and seasonal shifts in solar angle, and atmospheric attenuation. It is implemented as an ArcView v.3.2 GIS extension.

The direct, diffuse and global solar radiation values at a given location and time are computed using the 'sunmap' and the 'skymap'. The sunmap is a raster map which provides the direct component of the solar radiation: it uses the same hemispherical projection as the viewshed. To obtain the sunmap, the amount of radiation that reaches the Earth's surface is computed based on a radiative transfer model. The skymap is also a raster map but shows the diffuse solar radiation component; it also uses the same hemispherical projection as the viewshed. To obtain this raster, the incident solar radiation coming from any part of the sky was computed by assuming the diffuse radiation to be isotropic.

In order to obtain the direct and diffuse solar radiation, Solar Analyst needs two parameters related to the sky conditions as input: the transmissivity and the diffuse rate. These two parameters were estimated using data from field radiometric stations located in the area of study. Finally, based on the viewshed, the sunmap and the skymap, an estimation of the solar direct and diffuse solar radiation values was computed. The global radiation was obtained by adding the diffuse and direct radiation (Fu & Rich 2000). Figure 2 presents an outline of these processes.

3. Experimental data

The evaluation of the performance of Solar Analyst estimates has been carried by using experimental data collected in an area in south-eastern Spain, within the Sierra Nevada Natural Park (Figure 3). Sierra Nevada is the biggest such park in Spain, accounting for more than 86,000 ha. It has a complex topography, with elevations ranging from 500 to 3482 m (Mulhacén peak). The climate is that of a typical middle and high Mediterranean mountain environment, with dry hot summers, cold winters, and relatively high precipitation in autumn and spring. Precipitation during winter is mainly in the form of snow. There is a large range of vegetation types, including over 60 plant species that are found only in the Sierra Nevada.

Fourteen meteorological stations are located on the northern side of the Park, in an area covering 10 × 5 km^2 which is representative of the complex topography of the Park (Figure 4). The locations of the stations cover a wide range of elevations (from 1100 to 1700 m), aspects and slopes (see Table 1).

HOBO (Onset Corporation, Bourne, Massachusetts, USA) data-loggers were employed to collect temperature (Onset TMC6-HB probe) and global and photosynthetically-active radiation radiation data (Licor 200-SZ and Licor 190SZ radiometers, Lincoln, Nebraska, USA). An annual calibration and intercomparison of the sensors is carried out. The estimated instrumental error is less than 3%.

All data were recorded every 2.5 minutes. In the present study, data for every month in the period from May 2002 to May 2004 were analysed, thereby covering all the

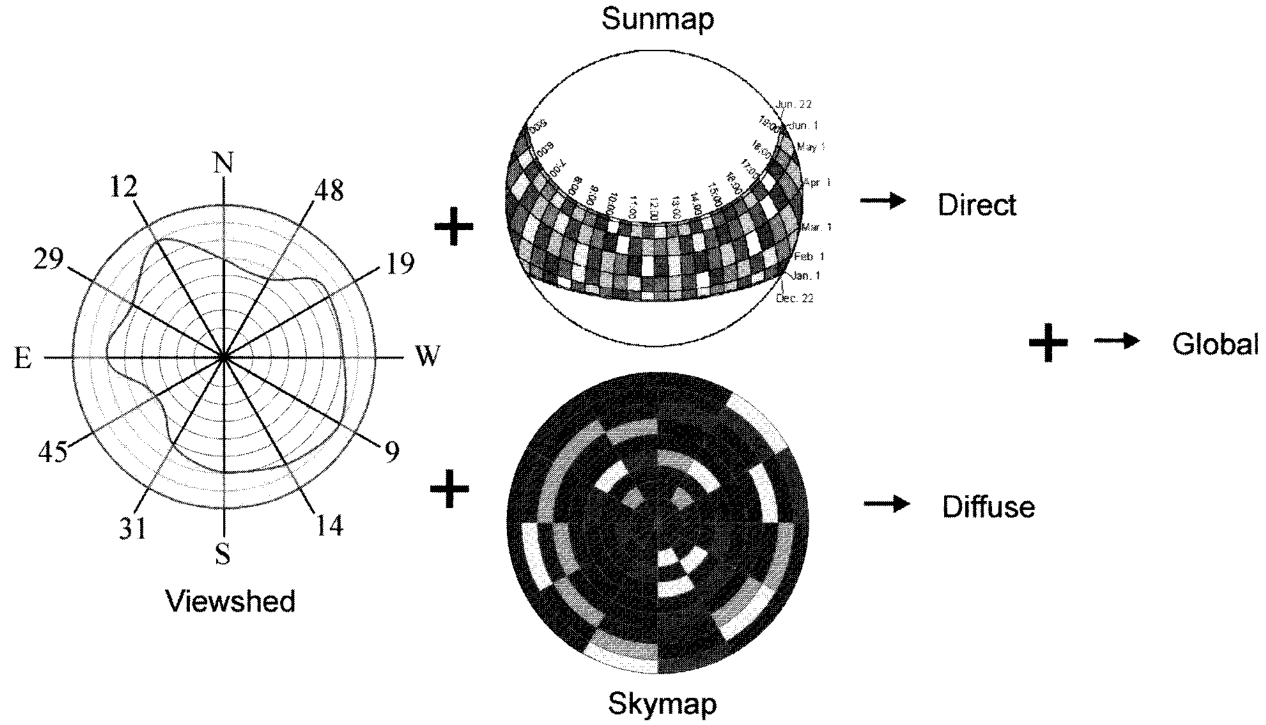

Figure 2. *The hemispheric vision overlaps with the insolation (direct and diffuse) maps calculated for a specific time. By overlapping both diagrams, the estimated direct, diffuse and global radiation at this site can be computed. (Based on Fu & Rich 2000.)*

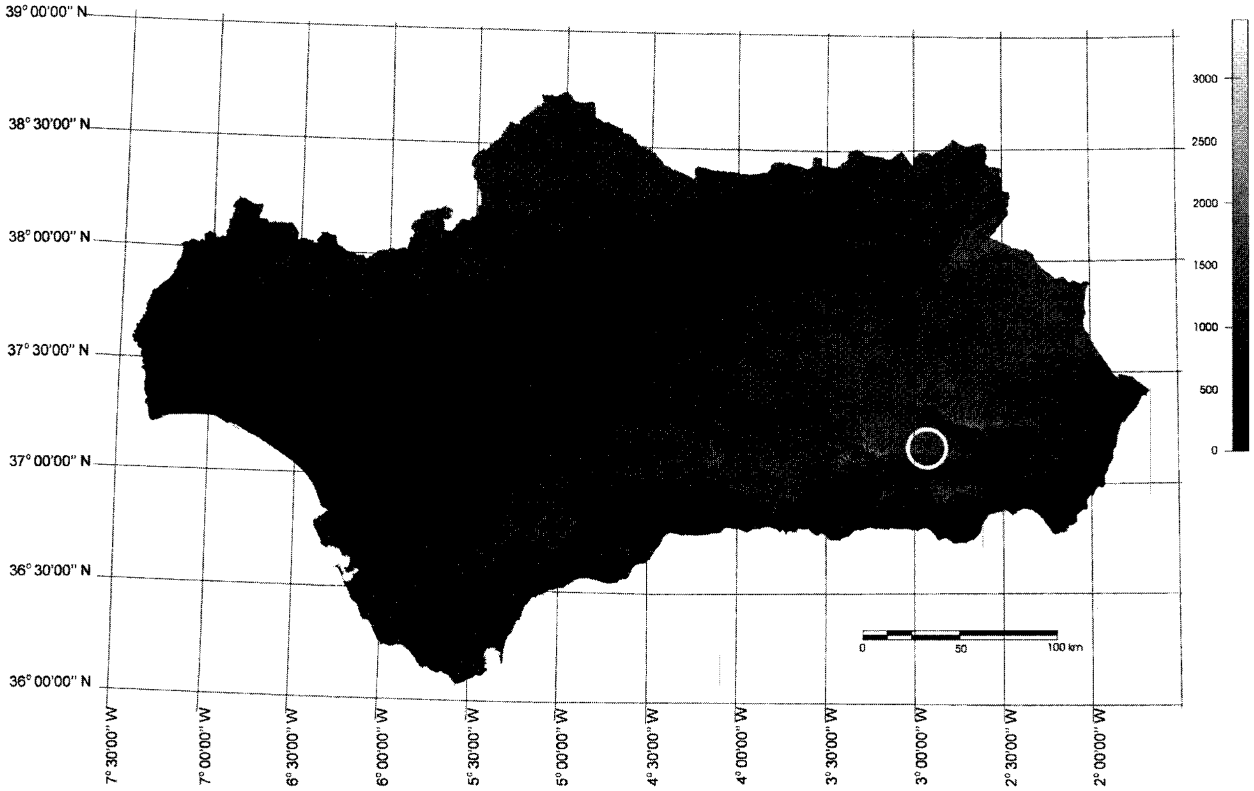

Figure 3. *Location of the study area: the Sierra Nevada Natural Park (Andalusia, Spain).*

natural annual changes in solar radiation. This temporal diversity and the different topographic characteristics of the station locations ensured the coverage of a wide range of climatic situations. A 20 m resolution DEM was employed and covered an area measuring $20 \times 20\ km^2$, which contained the $10 \times 5\ km^2$ study area, thus allowing the horizon effects on the estimated solar radiation to be taken into account properly.

Table 1. *Characteristics of the network of radiation-monitoring stations. UTM = Universal Transverse Mercator (coordinates).*

Station number	Lat (N)	Long (W)	Coord. (UTM)	Elevation(m)	Slope (degrees)	Aspect
1	37°08′52″	2°58′34″	(502130. 4111284)	1670	23.32	SE
2	37°08′50″	2°58′29″	(502243. 4111212)	1647	18.69	S
3	37°08′47″	2°58′17″	(502532. 4111109)	1623	19.63	S
4	37°08′05″	2°58′25″	(502334. 4111674)	1562	10.61	SE
5	37°08′58″	2°58′13″	(502639. 4111461)	1568	11.40	E
6	37°08′58″	2°58′02″	(502905. 4111461)	1537	12.00	SE
7	37°08′59″	2°58′56″	(503062. 4111460)	1505	12.46	E
8	37°08′48″	2°58′45″	(503325. 4111154)	1460	9.23	S
9	37°08′47″	2°58′54″	(503111. 4111107)	1447	25.79	E
10	37°08′22″	2°58′36″	(503539. 4112190)	1301	5.58	NE
11	37°08′25″	2°58′25″	(503828. 4112280)	1276	3.85	E
12	37°08′29″	2°58′32″	(503658. 4112414)	1299	14.21	E
13	37°08′31″	2°58′16″	(505529. 4114325)	1156	0.00	Horizontal
14	37°08′34″	2°58′20″	(508391. 4116254)	1077	7.49	SE

Figure 4. *Location of the radiometric stations in the DEM (20 m resolution).*

4. Analysis and results

It is well known that over homogenous and flat landscapes the correlation of solar radiation data series measured from different locations is relatively high and decreases with the distance between stations (Aguado 1986; Long & Ackerman 1995). In these cases, classical interpolation methods provide good results for estimating solar radiation. Nevertheless, in complex topography the simple interpolation of data does not provide adequate estimates, and more complex models, which take into account the topographic characteristics, are needed to estimate the incident radiation properly (Tovar et al. 1995). To illustrate this phenomenon we have compared data measured at several stations. Figure 5a shows the instantaneous irradiance values (in

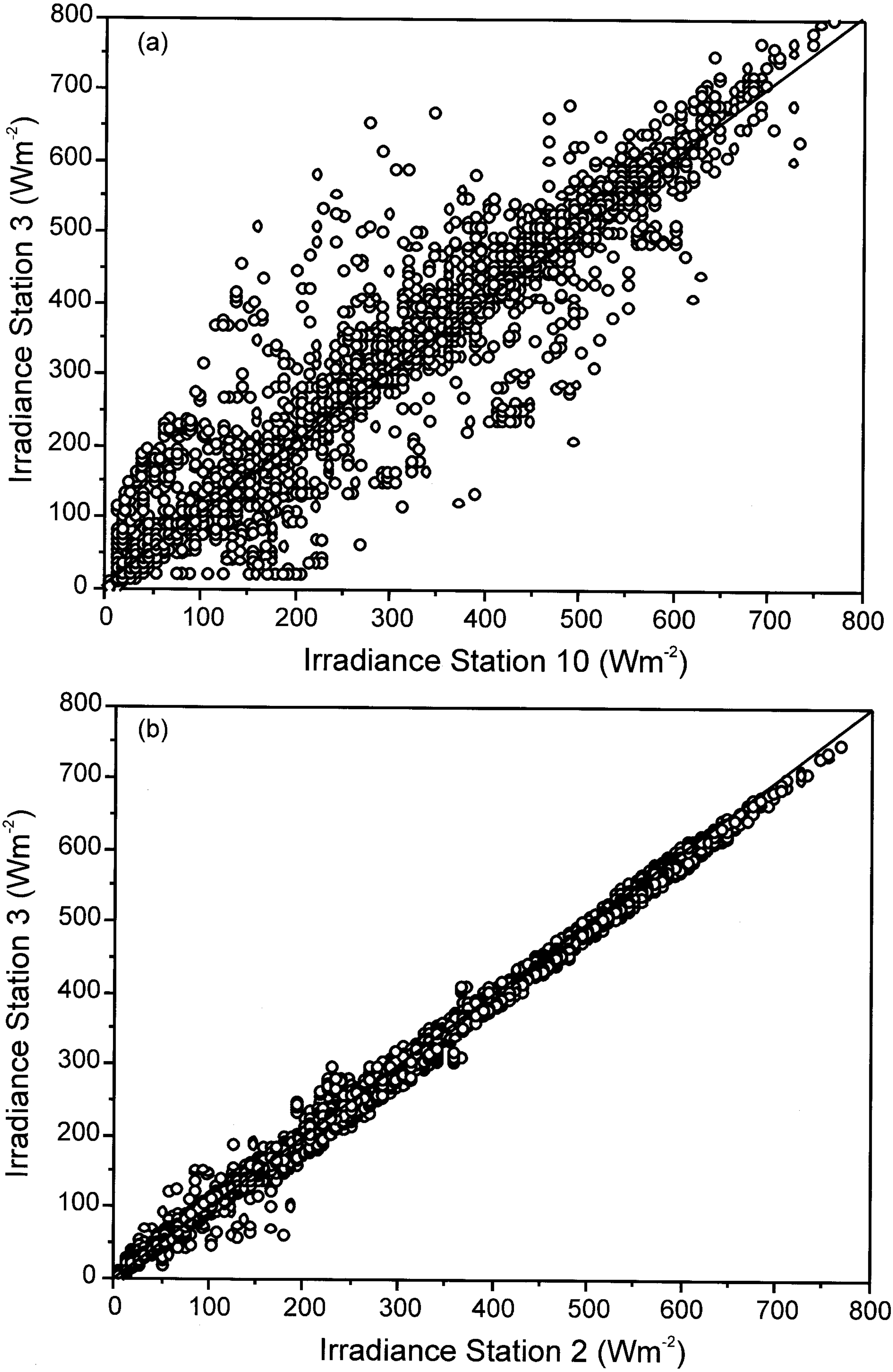

Figure 5. *Correlation between instantaneous irradiance values at two pairs of stations: (a) stations 3 and 10; (b) stations 3 and 2.*

Table 2. *Linear regression parameters computed based on the series in Figures 5a and 5b where A = intercept and B = the slope.*

Pairs of stations	Data number	A (Wm^{-2})	B	Standard deviation (Wm^{-2})	R^2
3 and 10	16022	2.29	1.03	67.54	0.86
3 and 2	16022	−0.19	0.99	6.41	0.98

Wm^{-2}) corresponding to two nearby stations (stations 3 and 10) with very different aspect and slope, while Figure 5b shows the values corresponding to two nearby stations (stations 3 and 2) with similar aspect and slope. All the values correspond to cloudless days in October 2003 and 2004. Figure 5a shows a wide dispersion of the data while Figure 5b shows similar values for both stations, which means that, in areas of complex topography, stations in close proximity can have very different radiation values. Table 2 shows the best lineal fit between these pairs of stations. The biggest differences in Figure 5 are found for values below 200 Wm^{-2}. Similar results are found when other pairs of stations are compared. Given the use of cloudless day data, these data correspond to low solar elevation angles (sunset and sunrise). This means that the artificial horizons induced by the topography play an important role in explaining the differences in the data of both stations. For high irradiance values, the differences between stations are lower, due to the low solar zenith angle. For these cases, the importance of topography in modifying the solar radiation is lower.

To sum up, this analysis shows that in complex topography the distance between stations cannot be used to estimate the incident radiation, but other topographic parameters (elevation, slope and aspect) strongly modify the solar radiation when moving relatively short distances.

A study has been conducted to evaluate the solar radiation estimates provided by Solar Analyst and compare them against experimental data. In order to do this, data for 12 cloudless days in 2003 and 2004 have been used – one day for every month of the year for all the meteorological stations in the network, providing a total of 168 daily irradiation values. The criterion to select the data was to take the cloudless day nearest to the 15th day of every month. The results are presented in Figure 6. A simple linear fit shows a slope value of 1.05, an intercept 2.23 MJ m^{-2} value,

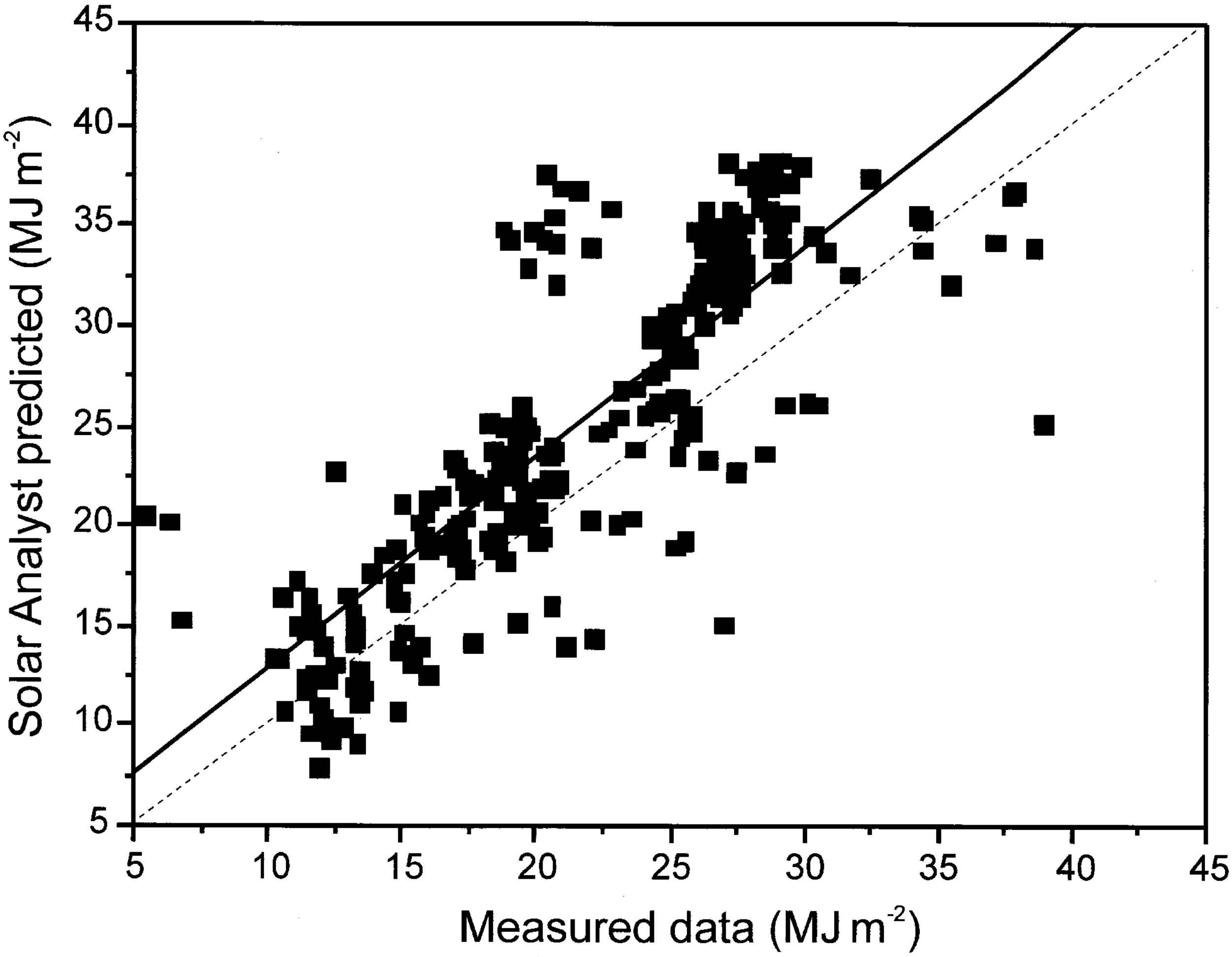

Figure 6. *Correlation between measured daily solar irradiation values and estimated values computed using Solar Analyst.*

Table 3. *Differences in the topographic parameters of the radiometric stations location measured in-situ and obtained based on the DEM.*

Station number	Measured elevation (a.m.s.l.)	DEM elevation (a.m.s.l.)	Differ. (m)	Measured slope (°)	DEM slope (°)	Differ. (°)	Measured aspect (°)	DEM aspect (°)	Differ. (°)
1	1659	1670	11	10	23.32	−13.32	45.0	150.5	−105.46
2	1669	1647	22	14	18.69	−4.69	225.0	191.7	33.27
3	1619	1623	4	13	19.63	−6.63	202.5	177.0	25.51
4	1558	1562	4	9	10.61	−1.61	135.0	115.7	19.29
5	1565	1568	3	5	11.40	−6.40	180.0	82.9	97.13
6	1532	1537	5	11	12.00	−1.00	90.0	151.9	−61.93
7	1505	1505	0	3	12.46	−9.46	180.0	81.9	98.13
8	1467	1460	7	19	9.23	9.77	180.0	180.0	0.00
9	1449	1447	2	19	25.79	−6.79	202.5	84.8	117.69
10	1305	1301	4	5	5.58	−0.58	45.0	39.8	5.19
11	1292	1276	16	15	3.85	11.15	157.5	68.2	89.30
12	1300	1299	1	8	14.21	−6.21	157.5	105.8	51.75
13	1188	1156	32	0	6.78	−6.78	0.0	3.0	−3.01
14	1091	1077	14	6	7.49	−1.49	157.5	154.7	2.85
Average of differences			5.07			−3.15			26.41
Standard deviation			11.95			6.74			62.59
Standard error			3.19			1.80			16.73

with a correlation $R^2 = 0.75$ and standard deviation of 4.3 MJ m^{-2}. Although the model provides relatively good estimates, it tends to overestimate the radiation values, and the scattering of the data is relatively high (see Figure 6). An additional analysis showed that a large part of this scattering is due to the DEM resolution. The topographic parameters obtained for the 14 stations based on the 20 m resolution DEM were compared with experimentally measured data: a GPS device was used to obtain altitude and an electronic clinometer to measure slope and aspect. The result (see Table 3) shows that the differences in elevation are relatively low, but differences in slope and aspect are relatively high. These differences strongly contribute to the scattering of the data, meaning that the DEM resolution plays a very important role in obtaining accurate solar radiation estimates.

Another possible source of error in the model estimates is the fact that the model does not take into account either the albedo or the multiple reflection that solar radiation undergoes before reaching the measuring point. This source of error is particularly important when snow cover is present, which often occurs in mountainous areas during winter.

5. Conclusions

The use of simple interpolation methodologies for estimating the solar radiation incident at the surface, based on measurements carried out at a few meteorological/climatological stations, does not provide a good estimation of solar radiation in areas of complex topography. The reason is that the topography causes significant variations in solar irradiation over short distances. The use of DEMs allows better estimates of the solar radiation to be obtained in these areas by taking into account the topographic parameters in radiation transfer models.

The Solar Analyst model in ArcView has been evaluated using experimental data collected from an area of complex topography in southern Spain. The model provides good estimates of the solar radiation, although it overestimates the solar radiation values, and the scattering of the estimates is relatively high. The analysis of the differences between the estimates and the experimental data shows that the resolution of the DEM plays an important role in explaining such differences. Another possible source of error is the fact that the albedo is not incorporated into the model.

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