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A comparative study of ordinary and residual kriging techniques for mapping global solar radiation over southern Spain

Husain Alsamamra, Jose Antonio Ruiz-Arias, David Pozo-Vázquez *, Joaquin Tovar-Pescador

Department of Physics, University of Jaén, 23071, Jaén, Andalusia, Spain

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ABSTRACT

This study presents a comparative analysis of the ordinary and residual kriging methods for mapping, on a 1 km × 1 km grid size, the monthly mean of global solar radiation at the surface in Andalusia (southern Spain). The region of study is characterized by a wide range of topographic and climatic characteristic, which allows properly evaluating the two methods. The experimental dataset includes 4 years (2003–2006) of data collected at 166 stations: 112 stations were used to train the models and 54 in an independent validation procedure. Overall, the ordinary kriging method provide fair estimates: RMSE ranges from 1.63 MJ m^{-2} day^{-1} (6.2%) in June to around 1.44 MJ m^{-2} day^{-1} (11.2%) in October. In the residual kriging procedure, we propose using an external explanatory variable (derived just based on a digital elevation model) that accounts for topographic shadows cast, and that is able to explain between 13% and 45% of the spatial variability. Based on the combined used of the elevation and the former external variable, residual kriging estimates shows a relative improvement in RMSE values ranging from 5% in the summer months to more than 20% in the autumn and winter months. Particularly, RMSE is 1.44 MJ m^{-2} day^{-1} (5.5%) in June and 1.31 MJ m^{-2} day^{-1} (10.2%) in October. Explained variance also shows a considerable improvement compared to the ordinary kriging method, with all the months showing R^2 values above 0.92. Results show that most part of these improvements is associated with a better estimation of the minimum values, particularly during the winter part of the year. It is finally concluded that the proposed residual kriging method is particularly valuable when mapping complex topography areas.

1. Introduction

Global solar radiation is an important climate variable with respect to many fields as agriculture or renewable energy applications. In these fields, spatially continuous data set (maps) are needed. Along the last decades three different methodologies have been used for mapping the solar radiation: the use of satellite estimates, the use of Geographic Information System (GIS)-based solar radiation models and, traditionally, the use of the well known geostatistical methods.

Regarding the satellite estimates, geostationary satellites may provide spatially continuous irradiance values. Processing of satellite data provides less accurate values (compared to ground measurements), but has the advantage of the large spatial coverage that can provide. For instance, the Meteosat Second Generation (the second generation of the European meteorological satellite) has a temporal resolution of 15 min and 2.5 km of spatial resolution. In spite of the strong improvement compared to the previous Meteosat generation, many applications still need a better spatio-temporal resolution and the value of the solar radiation estimates for complex topography areas is limited. Nevertheless, several works have shown the usefulness of the satellite estimates as additional information in interpolation techniques for solar radiation estimation in mountainous regions (Zelenka et al., 1992; Beyer et al., 1997).

The use of GIS-based solar radiation model for solar radiation mapping has been developed along the last decades. These models uses the topographic information contained in a digital elevation model (DEM) to determine topographic features such as elevation, surface orientation and shadow casting. Based on this information and different physical parameterization, these models are able to estimate the incoming solar radiation at every point of the DEM (Tovar-Pescador et al., 2006). Several models such as SolarFlux (Hetrick et al., 1993; Dubayah et al., 1995), Solei-32 (Miklánek and Mèszáos, 1993; Mèszáos and Miklánek, 2002), Solar Analyst (Fu and Rich, 2000), SRAD (Wilson and Gallant, 2000), and r.sun (Hofierka and Súri, 2002) have been developed in the last decade.

* Corresponding author at: Departamento de Física, Universidad de Jaén, Edificio A3, Campus Lagunillas, 23071, Jaén, Spain. Tel.: +34 953 212783; fax: +34 953 212838.
E-mail addresses: husain@ujaen.es (H. Alsamamra), jararias@ujaen.es (J.A. Ruiz-Arias), dpozo@ujaen.es (D. Pozo-Vázquez), jtovar@ujaen.es (J. Tovar-Pescador).

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Ruiz-Arias et al. (in press) provides an evaluation of some of these models. Recently, Pons and Ninyerola (2008) have proposed a new GIS-based solar radiation model, tuned with local measured meteorological data. The main problem of these models is that they need for external meteorological information (often difficult to obtain) to provide the solar radiation estimates. Particularly, depending on the model, meteorological parameters as the Linke turbidity, cloudiness, atmospheric transmittance, circumsolar coefficient or albedo, are needed.

The interpolation techniques allow obtaining spatially continuous databases from isolated-stations measurements based on spatially interpolation methods. There are two different groups of the interpolation procedures. The first one uses deterministic interpolation techniques, which use mathematical functions to calculate the unknown values based on the degree of similarity with respect to the known points and provides no reliability assessment errors of the predicted surface. Examples of these techniques are the spline-functions or weighted averages (Hulme et al., 1995; Zelenka et al., 1992). The second one is the stochastic methods, which uses both analytical and statistical methods to predict unknown values based on the spatial auto-correlation among data points and offers the reliability of the predicted surface (Burrough and McDonnell, 1998). Among these methods, one of the most widely used are the kriging methods (Webster and Oliver, 2001). The kriging methods have showed considerable advantages, compared to the deterministic interpolations procedures, in the estimation of the rainfall (Tabios and Salas, 1985; Buytaert et al., 2006) and the temperature (Jarvis and Stuart, 2001; Zhao Chuanyan et al., 2005). Regarding the solar radiation, Rehman and Ghori (2000) demonstrated the usefulness of the use of the kriging technique to estimate the global radiation in Saudi Arabia. In this study, the root mean square error (RMSE) of the estimates ranged from 0.5% to 1.7%. More recently, Ertekin and Evrendilek (2007) used the universal kriging for mapping daily global solar radiation in Turkey. Results showed that this procedure were reliable in predicting the spatial variability of the global solar radiation, with RMSE values ranging from 1.4 to 10.0 MJ m^{-2} day^{-1}.

The reliability of interpolation techniques is strongly dependent on the sample size (Hughes and Lettenmaier, 1981; Mubiru et al., 2006). Particularly, kriging may provide reliable estimates of climate variables, as the solar radiation, in homogeneous terrain with similar climate characteristics. Nevertheless, the reliability of the estimates decreases when the complexity of the topography increases or when the earth surface is heterogeneous (as along land-sea discontinuities). In such cases, stochastic interpolation processes may not provide meaningful spatially continuous estimates, since point-specific measurements can be affected by strong local variation. For the solar radiation, particularly, complex topography areas present a challenge. Discontinuity in elevation and surface orientation (slope and aspect), and shadows cast by topographic features can create strong local gradients in the solar radiation that interpolation processes may not properly account for.

Many techniques have been proposed to overcome this weakness. These techniques allow taking into account external variables that may provide complementary information for the interpolation and, therefore, compensate for the lack of data and the scarce sample size (Odeh et al., 1995). These external variables may be used locally or in the whole study area and, in most of the cases, are related to geographical or topographical characteristics. These characteristics are currently available across the world at 1 km × 1 km of resolution (for instance the USGS global data). There are numerous studies trying to identify external variables for temperature and precipitation (Chuvieco and Salas, 1996; Benzi et al., 1997; Hargy, 1997; Llasat, 1997; Menz, 1997; Jorge et al., 2003; Carrera-Hernández and Gaskin, 2007). A few also dealt with the solar radiation (Sen and Sahin, 2001; Uran and Yun, 2004). There are different ways in which the external variables can be taken into account in the kriging process. For instance, the information coming from the external variables can be considered during the interpolation process, using co-kriging methods (see Carrera-Hernández and Gaskin, 2007). This method is advantageous when the external variable is highly correlated to the studied variable (Gotway and Hartford, 1996), but becomes very complex when more than one covariables are considered (Ahmed and de Marsily, 1987). Instead of including the external information directly in the kriging process, it is possible to consider it during the first step, prior to the interpolation itself. There are different denominations for this technique, as '*kriging with a guess field*' (Ahmed and de Marsily, 1987) or '*residual kriging*' (Phillips et al., 1992; Martinez-Cob, 1996). We will use this last denomination hereinafter. Basically, in the first step, a multiple linear regression is fitted between the variable of interest and some external explanatory variables. Then, an ordinary kriging procedure is applied to the residuals of this multiple regression analysis. Finally, a map is obtained integrating both the multiple regression and the kriging results. This technique, although relatively simple, is powerful, since allows including in an easy way multiple sources of external information in the interpolation procedure that may compensates for the small sample size. The residual kriging procedure has been used in numerous works for precipitation and temperature estimation (Prudhomme and Reed, 1999; Ninyerola et al., 2000; Ustrnul and Czekierda, 2005).

In this work, we present an application of the residual kriging methodology for mapping monthly-averaged global radiation at the surface in Andalusia (southern Spain). The aim is to evaluate the potential usefulness of this methodology for mapping the solar energy resources in this region, characterized by a wide range of topographic and climatic characteristic. Particularly, a key part of this work is concerned with the identification topography-related external variables able to account for part of the observed solar radiation spatial variability and, then, useful to improve the reliability of the kriging estimates. The ordinary kriging method is also applied, to evaluate the improvement provided by the residual kriging method.

The paper is organized as follows. Section 2 describes the study region, the dataset and, finally, presents the methodology. Section 3 presents the results and, finally, some conclusions are highlighted in Section 4.

2. Methodology

In this section, the study area and the database used in this work are first introduced. Then, a brief description of the geostatistical methods used in this work is presented. A more detailed description of, particularly, kriging procedures can be found in (Burgess and Webster, 1980; Vic Barnett, 2004). Finally, at the end of the section, the models evaluation procedure is explained.

2.1. Study area

The region of the study is the area of Andalusia, in the southern part of Iberian Peninsula (Fig. 1), covering around 87,000 km^2. The region is located in a transition zone (latitudes 35°30′–38°30′N and longitudes 7°30′–1°30′W) from temperate to subtropical climates, with the Atlantic Ocean and the Mediterranean region in the southern bound. Two different parts, from the topographic point of view, can be considered in the region. The western part, covering around 30,000 km^2, is an almost homogeneous flat area, with about 100 m of mean elevation. On the other hand, the eastern part