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New types of simple non-linear models to compute solar global irradiance from cloud cover amount

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A B S T R A C T

Most simple solar radiation models are built with reference to a basic model calibrated for clear sky conditions. New models are built in this paper with reference to *two* basic models, calibrated for clear sky and overcast sky conditions, correspondingly. The models are illustrated with measurements data from five meteorological stations in Romania (South-Eastern Europe), where the ratio between the solar irradiance on overcast sky and clear sky, respectively, ranges between 0.27 and 0.55. A three-parameter model is used for both basic models. Three new types of regression models were developed from the two basic models. They are non-linear generalizations of the Angstrom–Savinov model. Their accuracy decreases by increasing the cloud cover amount. One model has been further tested. A set of regression coefficients has been obtained by fitting that model to all available data, for all stations. The model based on this set of regression coefficients has good accuracy in any particular station, when low and intermediate cloudy skies are considered. The model based on a set of regression coefficients obtained in a given station was tested in other stations. Its accuracy is good (or marginally, good enough) on skies with low and intermediate cloudy skies. Its accuracy is good for intermediate zenith angles, ranging between 30° and 70°.

1. Introduction

Clouds are the atmospheric constituents with the greatest impact on the level of solar radiation incident on the ground. A simple (direct) measure of cloudiness is the cloud cover amount. In case the spatial distribution of clouds is uniform and the cloud speed relative to the sun is high enough, the time period with shade on a given point on earth surface is proportional (in first approximation) to the percentage of sky covered by clouds (Orsini et al., 2002). Thus, a simple (indirect) measure of cloudiness is the sunshine duration (Essa and Etman, 2004). Empirical correlations have been proposed between solar irradiance/irradiation and one (or both) of these measures. Research on this topic has been stimulated by the fact that most weather stations register information about cloud cover amount while the number of meteorological stations measuring solar radiation is still limited. Thus, appropriate modeling may provide estimates for solar radiation with higher spatial resolution than that of the network of radiometric stations. About 50% of solar irradiance variance is explained by cloud cover amount while 70–85% is quoted against sunshine duration (Bennett, 1969; Muneer and Gul, 2000). Thus, models based on sunshine are considered to be more reliable (Muneer and Gul, 2000). However, visual estimations of cloud cover amount are easier to obtain than sunshine recordings (Raju and Karuna Kumar, 1982).

Kimball (1928) proposed the first empirical correlations between daily global solar irradiation and cloud cover amount. For early works and good reviews work on solar radiation models see Elnesr and El-Sabban (1964), Abbas and Elnesr (1974), Paal (1987), Davies and McKay (1989), Festa and Ratto (1993), and Curry et al. (1993). More recent results can be found, e.g., in Li and Lam (2001), Furlan et al. (2012), Armstrong and Hurley (2010), Muneer and Gul (2000), Trnka et al. (2005), Martins et al. (2008), Lengfeld et al. (2010), and Bilgili and Ozgoren (2011).

Most solar radiation models are built with reference to a basic model calibrated for clear sky conditions (see Section 4 for a specific case). For small values of the cloud cover amount there is usually fairly good agreement between observed and estimated solar radiation values but the accuracy of the estimated radiation declines in case of very cloudy skies (Iziomon and Mayer, 2002). Thus, these models are appropriate for places where the frequency distribution of the cloud cover amount is unimodal and peaked at lower values.

However, there are many places where the frequency distribution of cloud cover amount is peaked at higher values. For instance,

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analysis of 38 year measurements in Hong Kong showed that a peak of 30% is observed at a cloud cover amount value of 7 octas while the second most frequent cloud cover amount is 8 octas, accounting for about 20% (Li and Lam, 2001). Clear sky conditions occur for only 6% of the time. The authors concluded that, in contrast to the general perception that Hong Kong is a predominantly bright and sunny place, about half of the time the sky condition is either overcast or "very cloudy". For such places, models based on clear sky calibrations may have poor performance most of the time and using calibrations for overcast sky seems to be recommended. Overcast skies are much more self-differentiated than clear skies are. Indeed, they exhibit spatial inhomogeneities and fluctuations of geometrical characteristics (such as top bumps, gap or fractional coverage, shape or structure) and optical characteristics (local extinction, effective radius, ice crystal shape) (Benassi et al., 2004).

Methods which compute solar radiation by combining hourly observations of cloud conditions with sunshine data in order to determine the frequency of clear, partly cloudy and overcast skies have been already published (see Badescu, 2002; Armstrong and Hurley, 2010). They provide a more accurate prediction of the diffuse radiation under varying sky conditions and seem to perform well on climates where the clear sky is not the most common condition (such as the frequently overcast climates of Northern Europe).

New types of empirical models are proposed here. They are built with reference to *two* basic models, which are calibrated on clear and overcast sky conditions, correspondingly. Using built-in information about the extremes of the cloudiness regime may ensure better performance. Two main aspects are identified with the empirical models (Furlan et al., 2012). First, they should be based on *simple* functional dependence of solar irradiance/irradiation against cloud cover amount, among other regressors. Second, the empirical model, which is developed by using local data, should have applicability for other regions. The suitability of the empirical models for a particular location should be checked against local measurements. The variation of coefficients is expected to be small for those regions with similar "climate pattern". These aspects are addressed in this paper. The new models are illustrated with data from five Romanian meteorological stations.

2. Radiometric and meteorological databases

Table 1 and Fig. 1 show the five meteorological and radiometric stations of the Romanian National Meteorological Administration providing data for this work. Romania is located in southeast Europe, between 43°37′07″N and 48°15′16″N, and 20°15′44″E and 29°42′24″E. Its area is 237,500 km^2 of which 30% are mountains (heights over 800 m), 37% are hills and plateaus (heights between 200 m and 800 m) and 33% are fields. The territory of the country is halved by the Carpathians chain, which stands as a natural border between the three historical provinces: Moldavia (to east), Transilvania (to west) and Valahia (to south).

The radiometric stations of Table 1 are provided with Kipp and Zonen CM6B radiometers. The single measurement uncertainty is $\pm 5\%$. The temperature dependence of sensitivity is $\pm 2\%$ on the interval -20 to $+40$ °C. On a monthly basis the bias for CM6B ranges between – 2% and $+0.9\%$ (Myers and Wilcox, 2009). More information about definition of instrument uncertainty may be found in Gueymard and Myers (2009) and Myers (2009). The radiometers are checked twice per week and cleaned when necessary. The radiation measurement methodology is provided by standard procedures prepared at the National Meteorological Administration. Measurements are performed as follows. Solar irradiance (units: W/m^2) is measured at 1-min intervals. The series of irradiance values are averaged over 10 min, 60 min and 1440 min, respectively. Irradiation values (units: J) for 10 min, one hour and 24 h are obtained by multiplying the appropriate average irradiance values by the appropriate time duration.

Table 1
Romanian meteorological and radiometric stations.

Name	Station code	Latitude (°N)	Longitude (°E)	Altitude (m asl)
Timisoara	15,247	45.77	21.26	86
Galati	15,310	45.47	28.03	71
Iasi	15,090	47.17	27.63	103
Cluj-Napoca	15,120	46.78	23.57	417
Craiova	15,450	44.31	23.87	192

Fig. 1. Geographical position of five Romanian meteorological stations.

The radiometers are calibrated once per year, through shaded – unshaded measurements in clear sky days, and through direct irradiance measurements on a horizontal surface with reference to the Linke–Feussner etalon actinometer. The Linke–Feussner etalon is calibrated with reference to the national etalon, i.e. an Angstrom 702 pirheliometer with electric compensation. The national etalon is calibrated once at five years with reference to the World Radiometric Reference at Davos (Switzerland).

To eliminate spurious data and inaccurate measurements resulting from low solar altitude, only data collected at a zenith angle lower than 85° were used in analysis (Li and Lam, 2001; Rangarajan et al., 1984). Partial sky obstructions or shading of the sensors by natural or artificial structures is low and is not considered. Other tools to check the data quality, such as those provided by the HelioClim server have been not used. The radiation measurements were stamped at ground station every fix hour (i.e. 7.00, 8.00, etc. UTC).

The cloud cover amount N is estimated by eye by trained observers and reported in octas, with 0 allocated to clear sky and 8 to completely covered sky. The cloudiness is observed at one hour lag. The cloud cover fraction C is simply defined as $C \equiv N/8$. Most solar radiation models use C as a quantity associated with cloudiness.

The ground-based estimation of the cloud cover amount is subject to well-known errors (Harrison and Coombes, 1986; Badescu, 1990, 1991). Typical problems occur due to different observers. An overestimation of cloud cover can occur from perspective problems faced by the observers. Clouds obscure a greater fraction of the sky when viewed near the horizon than when viewed overhead. This effect is greater for moderate amount of cloud and vanishes for near overcast skies. For the Romanian