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Coupling satellite images with surface measurements of bright sunshine hours to estimate daily solar irradiation on horizontal surface

Selmin Ener Rusen [a,*], Annette Hammer [b,2], Bulent G. Akinoglu [a,1]

[a] Department of Physics, Middle East Technical University, Ankara 06531, Turkey
[b] Department of Energy and Semiconductor Research, Faculty of Physics, University of Oldenburg, Oldenburg D-26111, Germany

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ABSTRACT

Satellite images are heavily used for the estimation of solar irradiation at the Earth's surface. The accuracy yet should be improved to attain more reliable input values for the use of all types of solar energy systems. This paper presents two new alternative approaches to increase the estimation accuracy of daily solar irradiation by coupling the satellite images with surface bright sunshine hour measurements. Two different approaches are described for the estimation of global solar irradiation on daily base, by using the data for some locations in Turkey and Germany. These approaches are compared with the estimation of a satellite model (HELIOSAT), Angstrom models and ground measured daily global solar irradiation by using regressions and error analyses. For nine out of ten stations the relative RMSE values of the proposed models slightly decrease in the range of only 2% in comparison with the direct satellite model for the daily global solar irradiation. The results obtained for the new approaches did not considerably improve the performance of the satellite model. However, it is possible to recommend new coupled approaches to estimate daily global solar irradiation because of their simpler calculation procedure. The results are encouraging for the future works to use long and short-term satellite image data together with the surface measured data to estimate the solar irradiation values.

1. Introduction

Solar irradiation knowledge at the Earth's surface is necessary for optimization and performance analysis of all types of solar energy systems. The most accurate way of obtaining solar irradiance is certainly the use of ground-based measurements. However, the measurement network is not adequate and at many stations, the data taken is not quite reliable. Methods using geostationary weather satellites are profoundly progressing in recent years in estimating solar irradiance at ground level but these are indirect methods and not better than the models that use nearby surface measurements [1]. An advantage of the images taken from satellites is their large area coverage with high spatial and temporal resolution especially for the Meteosat Second Generation (MSG) satellites [2]. Therefore, it is important to increase the accuracy of such estimations and to this aim long term and relatively accurate surface measurements of some climatic parameters can be very useful [3].

This work begins by describing HELIOSAT which is one of the most popular methods for solar irradiance estimations that use the pixel values of the satellite images. This model calculates the cloud index (n) from the images and it uses clear-sky irradiance values, which are computed by some local information like Linke Turbidity, T_L. The method or the modified versions of it use statistical ways and empirical relations in their calculation procedure [2,4]. In the present study, we used a modified version of HELIOSAT for our analysis. Other mentioned methods are the statistical methods that use ground measurements that provide high performances for the estimation of global solar irradiance. Among them, the Angstrom type method [5] utilizes surface measured daily bright sunshine hour (s) values. These values are available in most locations all over the world. Detailed discussions are given in various references such as Martinez-Lozano et al. [6], Akinoglu [7,8].

The following sections describe the data and the methods used in the study. Two new models to couple the ground measurements (bright sunshine hours (s)) and the satellite derived cloud index (n) to attain higher accuracy in the estimations of daily global solar radiation are presented in Section 3. Using four stations in Turkey

* Corresponding author. Tel.: +90 312 210 3252.
E-mail address: eselmin@metu.edu.tr (S.E. Rusen).
[1] Tel.: +90 312 210 3252.
[2] Tel.: +49 441 798 3545.

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and six stations in Germany, we have compared surface measurements with the estimations of Angstrom type relations, HELIOSAT and with the coupled approaches of the present work which are given in the results and discussion part of the paper. Finally, consideration of the results in Section 5 concludes this work. The obtained results are encouraging for the future works to use long and short-term satellite image data together with the surface measured data to estimate spatially continuous daily global solar irradiation values.

2. Data and methods

The database of ground level global solar irradiation and sunshine duration were obtained from Turkish State Meteorological Service (TSMS) for selected stations in Turkey and Deutscher Wetterdienst (DWD) for the stations in Germany. Meteosat visible channel images and all HELIOSAT calculations were carried out at University of Oldenburg. Locations and altitudes of the selected stations are presented in Table 1. We used one-year data of 2004 for the stations in Turkey and 2006 for the stations in Germany.

2.1. HELIOSAT method

The principle of the HELIOSAT method is to use atmospheric clear sky and cloud extinctions, which are calculated separately. Cloud information is determined by Meteosat visible channel counts and then, clear sky irradiance is computed using a model for direct and diffuse irradiance. Detailed explanations of the HELIOSAT method are documented in the following references: Zelenka et al. [1], Beyer et al. [4], Cano et al. [9], Hammer et al. [2,10], Girodo et al. [11]. Here we only give a short description of the modified form that we utilized for the present work.

The HELIOSAT method makes use of the fact that a thick cloud layer correlates with a low cloud transmission and at the same time a high cloud reflectivity observed in space. This reflectivity is calculated from the broadband visible channel data. It is possible to derive a cloud index (n) from the relative reflectivity value ρ for each pixel as:

$$n = \frac{\rho - \rho_{clear}}{\rho_{cloud} - \rho_{clear}} \quad (1)$$

Here the relative reflectivity observed in space is calculated from the satellite pixel digital count C, the satellite instrument offset C_o and the extraterrestrial instantaneous irradiance G_{ext} as:

$$\rho = \frac{C - C_o}{G_{ext}} \quad (2)$$

The reference values of relative cloud reflectivity ρ_{cloud} and relative clear sky reflectivity of the ground-atmosphere system ρ_{clear} are calculated from the minimum and maximum values found in the time series of images of the scene under concern [12]. The calculations are carried out for hourly intervals.

To estimate the solar irradiation with the modified version of HELIOSAT, an empirical relation is used between the hourly clear sky index k^* and cloud index n [4]. This empirical relation may be defined in a simple form as:

$$k^* = 1 - n \quad (3)$$

Here k^* is defined as $G/G_{clearsky}$ where G is the hourly global irradiance values for the site of interest and $G_{clearsky}$ is the calculated hourly clear sky irradiance for the site using a clear sky model [2].

There are various models to calculate the surface global clear sky solar irradiation $G_{clearsky}$, based on different possible atmospheric and climatic inputs [13–15]. One of them is the currently used Dumortier clear sky model [16] which uses the Linke Turbidity, sun elevation, and the altitude of the site as parameters. Here, Linke Turbidity T_L describes the atmospheric extinction; we use the climatology of monthly values developed by Remund [17].

The hourly clear sky irradiance ($G_{clearsky}$) is calculated by Dumortier [16] as follows:

$$G_{clearsky} = G_{dn;clear} \cos\theta_z + G_{dif;clear} \quad (4)$$

where Θ_z is the zenith angle of the sun, $G_{dn;clear}$ is the clear sky direct irradiance model of Page [18] and $G_{dif;clear}$ is the clear sky diffuse irradiance model of Dumortier [16]. The daily totals of HELIOSAT clear sky irradiation can be obtained from the hourly values, $G_{clearsky}$ by simply summing over the day ($\Sigma G_{clearsky} = H_{clear,H}$ for HELIOSAT clear sky model).

For the hourly values of clear sky index k^* and cloud index, n the empirical relations hold:

$$k^* = \begin{cases} 1.2 & \text{for } n < -0.2 \\ 1 - n & \text{for } -0.2 < n \le 0.8 \\ 1.1661 - 1.7814n + 0.7250n^2 & \text{for } 0.8 < n \le 1.05 \\ 0.09 & \text{for } n > 1.05 \end{cases} \quad (5)$$

The relationship is simply $k^* = 1-n$ within the largest range of n values -0.2 and 0.8 and was given by Lorenz [19].

As described above, cloud transmission can be defined by the clear sky index k^* ($=G/G_{clearsky}$) as in Equation (3), $G_{clearsky}$ can be obtained using Equation (4) and then Equation (5) is used to obtain the hourly global solar surface irradiance G_{hourly}:

$$G_{hourly} = k^* G_{clearsky} \quad (6)$$

HELIOSAT is an hourly-based method and one can find the daily values simply by summing the calculated hourly values ($\Sigma G_{hourly} = H_{sat}$). Angstrom type models however are daily-based models and the simplest approaches are given in the following section.

2.2. Angstrom method

Bright sunshine hour is empirically correlated to the daily global solar irradiation in the Angstrom–Prescott relation [5,20] as:

$$K = \frac{H}{H_0} = a + b\frac{s}{S} \quad (7)$$

where H is the daily global solar irradiation and H_o is the daily extraterrestrial solar irradiation on a horizontal surface. The quantities s and S are measured daily bright sunshine hour and

Table 1
Geographical information of selected stations.

Selected stations	Latitude	Longitude	Altitude (m)
Ankara/Turkey	39.97 N	32.86 E	891
Bursa/Turkey	43.23 N	29.01 E	100
Afyon/Turkey	38.74 N	30.56 E	1034
Sinop/Turkey	42.03 N	35.15 E	32
Braunschweig/Germany	52.30 N	10.45 E	83
Bremen/Germany	53.05 N	8.80 E	24
Chemnitz/Germany	50.80 N	12.87 E	418
Norderney/Germany	53.72 N	7.15 E	29
Fichtelberg/Germany	50.43 N	12.95 E	1213
Wittenberg/Germany	51.88 N	12.65 E	105