USING SUNSHINE DURATION AND SATELLITE IMAGES TO ESTIMATE DAILY SOLAR IRRADIATION ON HORIZONTAL SURFACE

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Abstract

The use of satellite measurements for the estimation of solar irradiation at the Earth surface is rapidly increased in the 21st century. The accuracy of such estimations yet should be modified to attain more reliable input values for the use of all types of solar energy systems. This paper presents a new alternative approach aiming to increase the estimation accuracy of daily solar irradiation by coupling the satellite images with surface bright sunshine hour measurements. This approach is described for the estimation of global solar irradiation on daily base by using bright sunshine hour data for two regions, one in Turkey and one in Germany, respectively. Using one-year data, daily solar irradiation values for these two different stations have been calculated and standard error analyses are carried out to analyze the performance of the correlations. The results are compared with the estimation of a commonly used satellite model (HELIOSAT) and the Angstrom model using measurements of daily global solar irradiation.

1. Introduction

Solar energy, meteorology, and many climatic applications are directly related to the correct knowledge of solar radiation at the Earth's surface. Pyranometer measurements is the most accurate way of characterizing the solar resource of a given site (Dagestad, 2005). However, measurement network is not adequate and the data taken are not quite reliable in most stations. Satellite image based estimation methods are quite promising but they are indirect methods and not better than the models that use nearby surface measurements (Zelenka et al., 1999). Yet, these methods are still developing and the relevant satellite technology has been profoundly improving in recent years. An advantage of the images taken from geostationary satellites is their large area coverage with high spatial resolution (up to 1 km) and with sufficient temporal resolution (up to 15 minutes) especially for the second-generation Meteosat satellites (Beyer et al., 1996; Hammer et al., 2003; www.eumetsat.int, 2010). Information of these satellite images were used to develop models for the derivation of solar irradiance data by many researchers such as Cano et al. (1986); Beyer et al. (1996); Hammer et al. (2003). In the present study, we used a modified version of HELIOSAT method (Zelenka et al., 1999; Hammer et al., 2003; Girodo et al., 2006) for our analysis.

On the other hand, there are many methodologies for the estimation of solar irradiation on the Earth's surface using different surface measured climatic variables (Akinoglu and Ecevit, 1990a, 1990b). Among these methodologies, the methods using measurements of bright sunshine hours together with Angstrom type correlations are most commonly used. Recent evaluations on these types of correlations can be found in Akinoglu (2008). Here, we used linear Angstrom type monthly correlations to modify the HELIOSAT formalism to include a surface measured quantity in such a satellite-based application.

2. Methods

There are several models, which estimate surface solar irradiance based on geostationary satellite data (Beyer et al., 1996; Hammer et al., 2003; Dagestad, 2005; Hammer et al., 2001). One of them is the HELIOSAT method that is an estimation technique to infer the shortwave surface irradiance from satellite images by using a statistical procedure (Beyer et al., 1996; Hammer et al., 2003).

2.1 HELIOSAT Method

The HELIOSAT method has been developed to estimate hourly global horizontal irradiance at ground level using images taken in the visible range by the European meteorological satellite series, namely Meteosat (Hammer et al., 2003; Hammer et al., 2001; Dagestad, 2005). The HELIOSAT method was initially used by Cano et al. (1986) as an estimation technique for short wave surface irradiance from satellite images. Because of its relatively easy formalism, the HELIOSAT method is a popular algorithm widely used in operational schemes around the world. Over the years, it has been modified and improved several times by some researcher (Beyer et al., 1996; Hammer et al., 2003; Hammer et al., 2001).

The general idea of HELIOSAT is to use atmospheric and cloud extinctions separately. A measure of cloud cover is determined by Meteosat satellites visible channel counts. In the first step, the time series of clear sky irradiance is computed for the chosen stations. In the second step, a cloud index is derived from Meteosat images to take into account relative reflectivity calculation. Detailed explanations of the HELIOSAT method is documented in the following references: Beyer et al. (1996), Hammer et al. (1999, 2003). Here we only give a short description of the modified form that we utilized for the present work.

In HELIOSAT, the relative reflectivity *(ρ)* is calculated as:

$$\rho = \frac{C - C_o}{G_{ext}} \quad \text{(eq. 1)}$$

where G_{ext} is the hourly extraterrestrial irradiance outside of the atmosphere. Here, C is the pixel counts over the location of interest extracted from the Meteosat images, and C_o represents an offset and it is subtracted from the satellite counts measurements (Beyer et al., 1996).

Most important step was the definition of the cloud index n, calculated for each pixel (or a small matrix of pixels over the region) as:

$$n = \frac{\rho - \rho_{clear}}{\rho_{cloud} - \rho_{clear}} . \quad \text{(eq. 2)}$$

Here ρ_{clear} and ρ_{cloud} are the maximum and minimum values of the relative reflectivity assuming that they correspond to clear and overcast conditions, respectively (Beyer et al., 1996). To estimate the solar irradiation, an empirical form is needed between the clearness index k and cloud index n as defined above. That is, in the linear approximation, hourly clearness index k can be written as:

$$k = \frac{G}{G_{ext}} = \alpha n + \beta \quad \text{(eq. 3)}$$

where G is the hourly global irradiance values for the site of interest, α and β are empirical parameters to be determined using regression analysis with the ground data. As one can guess these parameters, would be site dependent and might be affected from the temporal variations of the atmospheric conditions (Dagestad, 2005).

In the modified version, instead of clearness index k, a clear sky index k^* was used (Beyer et al., 1996). It was defined as:

$$k^* = \frac{G}{G_{clearsky}} \quad \text{(eq. 4)}$$

where $G_{clearsky}$ was a calculated hourly clear sky irradiance value of the site using a clear sky model. In their method, Hammer et al (2003) calculated $G_{clearsky}$ as follows:

$$G_{clearsky} = G_{dn;clear} \cos\theta_z + G_{dif;clear} \quad \text{(eq. 5)}$$

where Θ_z is the zenith angle, $G_{dn;clear}$ is the clear sky direct model of Page (1996) and $G_{dif;clear}$ is the clear sky diffuse irradiance model of Dumortier (1995). These models use the monthly Linke Turbidity factor from a database produced by Dumortier (1998). The daily totals of clear sky irradiation can be obtained from the hourly values, $G_{clearsky}$ by simply summing over the day.

As described above cloud transmission can be defined by the clear sky index k^* which is the ratio of the actual surface irradiance G and the clear sky irradiance $G_{clearsky}$ from Eqn. (4), and it is correlated with the cloud index n (Hammer et al., 2003). Eqns. (4) and (5) are then used to obtain the hourly surface irradiance G_g:

$$G_g = k^* . G_{clearsky} \quad \text{(eq. 6)}$$

Hammer et al. (2003) using the data of 23 locations from Europe correlated the hourly values k^* with n and they obtain the empirical relations:

$$k^* = \begin{cases} 1.2 & n < -0.2 \\ 1-n & n \in [-0.2, 0.8] \\ 2.0667 - 3.6667n + 1.6667n^2 & n \in [0.8, 1.1] \\ 0.05 & n > 1.1 \end{cases} \quad \text{(eq. 7)}$$

The calculation procedure is explained in details in reference: Hammer et al. (2003).

2.2 Angstrom Method

In most of the applications, Angstrom type equations are used to estimate the daily or monthly average daily global solar radiation (Akinoglu, 2008). In this form, regression coefficients a_i and b_i are calculated by using the linear correlation:

$$\frac{H}{H_o} = a_i + b_i \frac{s}{S} \quad \text{(eq. 8)}$$

called Angstrom-Prescott relation (Angstrom, 1924; Akinoglu and Ecevit, 1990a, 1990b; Akinoglu, 2008). The empirical values a_i and b_i are site dependent Angstrom coefficients for each month 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 daily bright sunshine hours and day length, respectively. Angstrom coefficients have been derived for many locations all over the world and are frequently used. Different types appeared in the literature and reviews and detailed information are presented in references (Akinoglu, 2008; Martinez-Lozano, 1984; Akinoglu, 1991). The calculation procedures of H_o and S can be found in reference Duffie and Beckman (1991).

Values of s were measured by using Campbell-Stokes heliographs, and H was measured by using pyranometer. The sunshine recorders do not work efficiently during the low altitude of the sun. Therefore, we used the modified day length S_o (day length for zenith angle $\leq 85^o$) instead of the daylength S, to consider the fraction of the day during which the solar zenith angle is greater than 85 degree. This calculation procedure is given by Hay (1979):

$$S_o = \frac{\arccos\left[(\cos 85 - \sin\varphi \sin\delta)/\cos\varphi \cos\delta\right]}{7.5} \quad \text{(eq. 9)}$$

3. Data and Models

3.1 Database

Ground level global solar radiation H and sunshine duration s observation data were obtained from Turkish State Meteorological Service (TSMS) for the stations in Turkey and the German Meteorological Service (DWD) for the stations in Germany.

The satellite images were obtained from Meteosat Second Generation (MSG) satellite and all calculation procedures for the cloud index applied to these images were carried out in Institute of Physics ,University of Oldenburg. The values for cloud index n, clear sky irradiance $G_{clearsky,}$ and surface irradiance $G_{global,}$, are calculated as a time series of hourly values. In all calculations, these hourly values of $G_{clearsky}$ and G_{global} were used to calculate the daily totals directly by summing. The daily clear sky index K^* is defined as the ratio of the daily totals of actual surface irradiance (ΣG) and the daily totals of clear sky irradiance ($\Sigma G_{clearsky}$). In addition, the daily averages of the cloud index, n_{avg} values were calculated for the basis locations of Turkey to use for direct daily estimations. Longitude, latitude and altitude information of all basis stations and the neighbor stations are given in Table 1. The basis stations are used for the derivation of model parameters. These models are then tested on the neighbor stations in a distance of 150 km to 350 km.

Tab. 1: Locations geographical information

Basis Stations		Latitude	Longitude	Altitude (m)
	Ankara/Turkey	39.97 S	32.86 E	891
	Bremen/Germany	53.05S	8.80E	24
Neighbor Stations	Afyon/Turkey	38.74 S	30.56 E	1034
	Braunschweig/Germany	52.30S	10.45E	83
	Wittenberg/Germany	51.88S	12.65E	105

3.2 Models and Calculations

We analyzed and compared the measured and estimated daily global solar irradiation values for all the data sets. Different procedures were adopted to link the surface bright sunshine measurements to satellite based procedures. Here, we present a new approach *referred to as* H_{model} that have the best performance.

3.2.1 H_{model}

The Angstrom-Prescott relation was used to calculate the daily clear sky radiation on the horizontal surface. In Eqn. (8), we have chosen modified day length S_o. If we take s/S_o = 1, the result is the daily clear sky radiation on horizontal surface; that is:

$$H_{clear} = H_o \left(a_i + b_i\right) \quad \text{(eq. 10)} .$$

These values of H_{clear} can either be calculated using one yearly pair of a and b or by using 12 pairs a_i and b_i for 12 months. The regression analysis of the calculated values of H_{clear} and the daily summation of $G_{clearsky}$ ($\Sigma G_{clearsky}$ from Eqn. (5)) for the period of one year for one location Ankara of Turkey are given in Fig. 1.

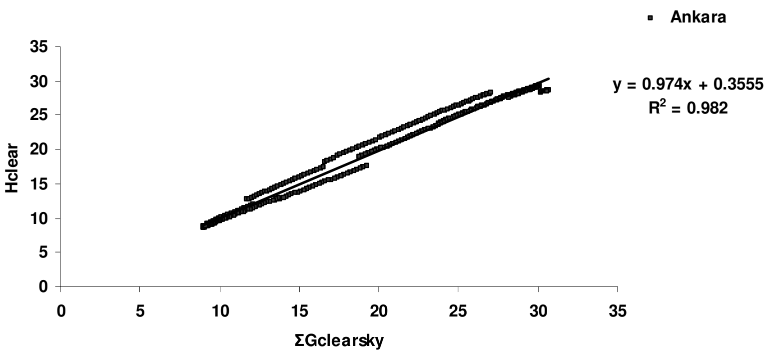


Fig. 1: Relation between H_{clear} and $\Sigma G_{clearsky}$ used in the regression analysis for Ankara.

Furthermore, it is possible to take the daily average values of the hourly cloud index in Eqn. (2) (n_{avg}) to find the daily global solar radiation. In writing this expression, we made use of hourly Eqn. (7) by assuming that the correlations for the daily averages follow a similar trend, which is ($1-n_{avg}$). In order to clarify this assumption, linear correlations between daily clear sky index K^* and daily average cloud index n_{avg} was investigated. Some differences were observed when we compared the results of hourly and daily data sets. In hourly considerations, the simple form ($1-n$) is good for k^* between the ranges -0.2 and 0.8.

Likewise, we also obtained new correlations for each station using the daily-based data sets. The results showed that there were slightly different relations between K^* and n_{avg}. The regression relation results were $0.99-0.93n_{avg}$ for Ankara and $1.00-1.02\ n_{avg}$ for Bremen. They seemed better in the calculations of K^*, in the widest range mentioned above, for Ankara and for Bremen. The regression results will be presented in the followings.

To determine a simple and accurate way to calculate daily solar irradiation from satellite images, H_{clear} was tested instead of $\Sigma G_{clearsky}$ in Eqn. (6). The motivation was the very similar results shown in Fig.1 as these two values have high correlation. In fact, the values of the correlation coefficients R^2 are larger than 0.98 for all the stations for $\Sigma G_{clearsky}$ and H_{clear}. In summary, to follow a similar procedure as in the hourly calculations, H_{clear} and the daily clear sky index K^* can be written in open form, using Eqn.(10) as a new approach for daily calculations can be written as:

$$H_{model} = (1 - n_{avg}).(a_i + b_i)H_0 \quad \text{(eq.11)} \quad .$$

Using the daily base regression analysis between K^* and n_{avg} , the ranges of -0.2 and 0.8, Eqn. (11) are rewritten in the form of Eqn.(12) for Ankara (Turkey) and Eqn.(13) for Bremen (Germany) as:

$$H_{Ankara_{fit}} = (0.99 - 0,93\,n_{avg}).(a_i + b_i)H_o \quad \text{(eq.12)} \quad ,$$

$$H_{Bremen_{fit}} = (1,00 - 1,02\,n_{avg}).(a_i + b_i)H_o \quad \text{(eq. 13)} \quad .$$

Note that a_i's and b_i's are monthly-based Angstrom coefficients of the stations under consideration derived from surface s measurements.

To verify this simple methodology, we used coefficients of the selected basis stations to estimate the values of H for other nearby stations. We used these two results of Ankara and Bremen to estimate daily solar irradiation for Afyon, a neighbor station in Turkey and two neighbor stations Braunschweig and Wittenberg in Germany, respectively. The values of the regression coefficients and their linear correlation coefficient R^2 are listed in Table 2.

4. Methodology and Research Results

To analyze the performance of the correlations, we used the one-year data for five stations from Turkey and Germany (Table 1). Table 2 gives the regression analysis results between calculated and measured solar irradiation for the two basis stations of interest. These approaches are denoted as H, H_{sat}, $H_{model,}$ and H_{fit}, which are explained below;

I. H is the calculated daily global solar irradiation on horizontal surface from Eqn. (8) (a_i and b_i are monthly varying values),
II. H_{sat} is the daily global solar irradiation on horizontal surface from satellite calculation,
III. H_{model} is the calculated daily global solar irradiation on horizontal surface from Eqn. (11),
IV. H_{fit} is the calculated daily global solar irradiation on horizontal surface from fitting process Eqn. (12-13).

The unit is identical in all calculations and it has been taken as MJ m^{-2} day^{-1}. The regression results together with regression coefficient R^2 are tabulated in Table 2. As it has been mentioned before, in the satellite derived estimations, use of the surface measurements may lead to obtain better results. It seems that introducing surface data through a_i and b_i to a simple satellite derived model (with $1\text{-}n_{avg}$ in the widest range column seven may lead quite similar results compared with H_{sat}) does not result considerable improvement in the estimations of the daily values. However, use of a_i and b_i obtained from surface data instead of $\Sigma G_{clearsky}$, with satellite image derived cloud index n_{avg}, is an easier way (because there is no need to use hourly $G_{clearsky}$ values) and gives quite satisfactory results for daily estimations.

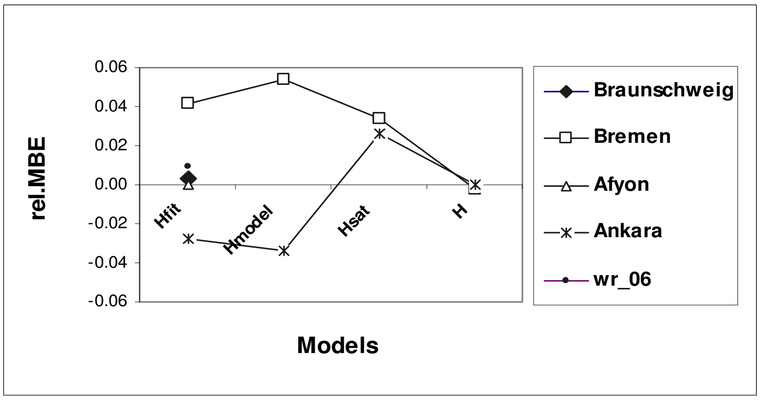
As explained earlier, we also tried the regression relations Eqn. (12-13) instead of the relation of Eqn. (11). To verify the use of these relations, equation of Ankara, Eqn. (12) is used for the neighboring province of Afyon. In the same manner, the result of Bremen Eqn. (14) is used for the Braunschweig and Wittenberg to estimate daily solar irradiation. The results showed that it is possible and satisfactory to use the correlations like Eqn.(12) and Eqn.(13) for nearby regions for daily calculations. R^2 values of the regressions between the measured and calculated H values of Afyon, Braunschweig, and Wittenberg with the correlations obtained from neighbors (Ankara and Bremen) were high and same as the R^2 values of the neighbors themselves. That is, R^2 values are 0.95 for Afyon and 0.96 for Braunschweig and Wittenberg.

Tab. 2: Comparison of the calculated daily results of the models with measurements *H* (MJ/m2).

	$H=(a_i+b_i\ .s/S)\ .\ H_o$		Hsat		$H_{model} = (1\text{-}n_{avg})\ .\ H_{clear}$		H_{fit}	
Stations	**f(x)**	**R2**	**f(x)**	**R2**	**f(x)**	**R2**	**f(x)**	**R2**
Ankara	0.98x+0.36	0.98	0.94x+1.44	0.98	0.94x+0.46	0.97	0.92x+0.97	0.97
Bremen	0.98x+0.15	0.98	1.01x+0.21	0.98	0.97x+0.80	0.97	0.97x+0.67	0.97

To identify the performance of models, standard error analyses are also carried out. Mean bias error (MBE) and root mean square error (RMSE) values were calculated on a yearly base for the selected stations. The results were good and we give the results for relative MBE and RMSE. For the whole period of the study, RMSE and MBE values are found to be small for H, which means that the estimations of these models are good. In addition, relative MBE and RMSE values of the other models are almost in the same range as can be observed from Fig.3. Estimations for the nearby stations (Afyon, Braunschweig, and Wittenberg) are also satisfactory as shown in Fig. 3.

a)



b)

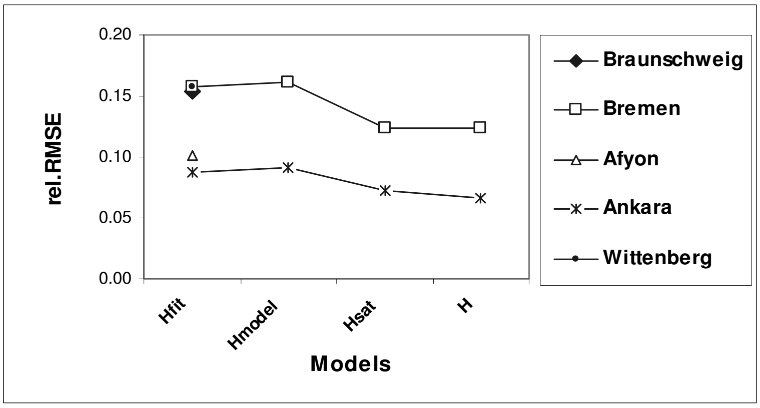


Figure 3. (a) Yearly relative MBE and (b) yearly relative RMSE among calculated models and ground measurement of daily global solar radiation data for the selected stations for one year. Relative values were calculated by dividing MBE and RMSE to the average of annual ground data.

5. Conclusion and Comments

In this report, the results from the empirical study of the estimations of daily global solar irradiation with satellite based and ground measurement based calculations were summarized. Furthermore, the new approach of coupling surface data with satellite images about estimations of daily global solar irradiation was presented.

The overall conclusions are as follows:

1) The results are examined and it is found that the error values of daily irradiation estimations of the new approach are found to be comparable with the daily estimations obtained from hourly satellite model. Use of $\Sigma G_{clearsky}$ for daily calculations is not necessary. Instead, $H_{clear} = (a_i+b_i)H_o$ can be used.
2) Instead of $1\text{-}n_{avg}$ (derived for hourly based calculations), new regressions for nearby stations may result in improvement in the estimations.
3) Direct use of present approach (surface measured bright sunshine hours s) for the daily estimations seems easier to apply instead of hourly-base calculations, because there is no need to use Linke turbidity, direct and diffuse irradiance, etc. However, it should be noted that this approach of coupling surface measurement to satellite values needs further verifications and modifications.

Consequently, present results showed that it is possible to recommend hybrid approaches in the satellite based daily solar irradiation estimation models. 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 in a simpler way within an acceptable accuracy.

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