International Scientific Journal
Environmental Science
http://environment.scientific-journal.com

The performance evaluation of a new model which based on bright sunshine hours and satellite imagery, for the estimation of daily global solar radiation for two locations in Turkey

Selmin ENER RUSEN
Department of Energy Systems Engineering
Karamanoğlu Mehmetbey University
Karaman, Turkey
Selmin.enerrusen@gmail.com

Abstract—**Measurements of the accurate global solar radiation at the Earth surface are needed to use in the researches for solar energy applications and for climate change and variability studies. Surface global solar radiation measurements are accurate enough but expensive to install the necessary instruments and such data are rare. Therefore, satellite images are used commonly in order to derive spatially continuous accurate solar radiation maps on the surface of the Earth. These images are very important for a good evaluation; but they are insufficient alone to use for the accurate estimates. In fact, they can indirectly support the accurate estimations of solar radiation at the Earth surface. In this study, we present the performance analysis and evaluation of a new developed model for estimation of the global solar radiation, based on the surface measured data (bright sunshine hours) and on the information acquired from the satellite images. The performance of the new model for the two different climatic zones of Turkey is analyzed; namely for two locations (Ankara and Erzurum). The analysis is carried out for typical continental climate characteristics of Ankara and cold and snowy climatic characteristics of Erzurum. Using the data for 12 months of a year, a preliminary study has been carried out for selected stations which produced important information for an extended work. Results can be used either to increase the performance of the models or to analyze long-term climate change studies with more accurate estimates.**

Keywords—Solar radiation; new coupled model; bright sunshine hours; satellite images.

I. Introduction

Solar energy, meteorology, and many climatic applications are directly related to the solar radiation at the earth's surface. Especially the correct knowledge of solar radiation as a climate variable observed at ground level, on a horizontal surface and integrated over the whole spectrum, have direct effects on life on Earth.

It is known that solar radiation is done by two main approaches. First is ground level measurement with a pyranometer and second is the estimation methods. Ground level solar radiation measurement is the most accurate method for characterizing the solar resource of a given site but they are expensive, and such data are rare[1]. Therefore, a number of estimation models are developed. The most popular one of is the Ångström-Prescott Method [2]. The general idea of this method is to deal with daily bright sunshine hourly values (***s***) and solar radiation correlations. Another estimation method is the satellite-derived solar radiation. It has become a worthy tool for quantifying the solar radiation at ground level for a large area. Generally, geostationary satellites which are rotating around the earth at the same speed as the earth are used for this kind of estimation method. They are several geostationary satellites all over the world and orbiting at about 36000 km. Also, they can offer a temporal resolution of up to 15 minutes and a spatial resolution of up to 1 km [3]. Images taken from these geostationary satellites are very important source to estimate solar radiation at the earth's surface [4]. Reference [5] carried out one of the earliest works for solar irradiation estimations using the pixels of the geostationary satellite images taken by Meteosat satellite which operate over Europe and Africa. The simple formulization that they developed is named as HELIOSAT. This method or its modified versions are used by many research teams [6]–[10].

In this study, we present the performance analysis of the new coupled model for the estimation of daily global solar radiation for the approximately same latitudinal position with different climates in Turkey. Using the data for one year period, in a preliminary study has been carried out for Ankara and Erzurum.

II. Methods

A. Angstrom Method

In most of the applications, Angstrom type equations are used to estimate the daily or monthly average daily global solar radiation [11]. In this form, regression coefficients ***a*** and ***b*** are calculated by using the linear correlation:

$$\frac{H}{H_o} = a + b\frac{s}{S_o} \quad (1)$$

which is named as Angstrom-Prescott relation [2], [6], [12]–[14]. The empirical values ***a*** and ***b*** are called Angstrom coefficients and are site dependent. ***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_o (day length for zenith angle $\leq 85^0$) [15] are daily bright sunshine hours and modified day length, respectively. These correlations exist for many locations all over the world and were utilized heavily. Values of ***H*** and ***s*** were obtained by Campbell-Stokes heliographs.

B. HELIOSAT Method

HELIOSAT method has been developed to estimate hourly global horizontal solar radiation at ground level using images taken in the visible range by the European meteorological satellite series, namely Meteosat [14], [16], [17]. The HELIOSAT method was initially used by Cano, Monget, Albuisson, Guillard, Regas and Wald [5] as an estimation technique for short wave surface radiation from satellite images. Because of its relatively easy formalism the HELIOSAT method is a popular algorithm widely used in operational schemes around the world [6]. Over the years, it has been modified and improved several times by some researchers [1], [6], [16].

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 are 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: [10], [16], [18]. 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:

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

where G_{ext} is the hourly extraterrestrial irradiance outside of the atmosphere. Here, C_o represents an offset and it is subtracted from the satellite counts measurements [10].

Most important step was the definition of the cloud index ***n***, calculated for each pixel as:

$$n = \frac{\rho - \rho_{clear}}{\rho_{cloud} - \rho_{clear}} \quad (3)$$

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 [10]. 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:

$$k = \frac{G}{G_{ext}} = \alpha n + \beta \quad (4)$$

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 [6], [19].

In the modified version, instead of clearness index k, a clear sky index ***k**** was used [16]. It was defined as:

$$k^* = \frac{G}{G_{clearsky}} \quad (5)$$

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[10], [20] calculated $G_{clearsky}$ as follows:

$$G_{clearsky} = G_{dn;clear}\cos\theta_z + G_{dif;clear} \quad (6)$$

where Θ_z is the zenith angle, . $G_{dn;clear}$ is the clear sky direct and $G_{dif;clear}$ is the clear sky diffuse irradiance. 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. (5), and it is correlated with the cloud index ***n***. Eqns.(5) and (6) are then used to obtain the hourly surface irradiance G_g:

$$G_g = k^* . G_{clearsky} \quad (7)$$

The calculation procedure is explained in details in several references [6], [9], [10].

C. New Coupled Model

Many methods and models to estimate global solar radiation were found in the past. In recent years, studies on combining satellite and ground-based methods in order to estimate global solar radiation have been carried out [6], [7], [21]. This new coupled model has been developed with the aim of a combination of ground measurements of ***s*** values and satellite-image driven daily average of hourly cloud index $\boldsymbol{n_{avg}}$. Studies have demonstrated that the estimation accuracy of daily solar radiation increase with this model [6]. A detailed description of this approach will be provided below via some formulas.

New coupled model is mainly depended on a basic energy conservation principle detailed by some researchers [22], [23]. In addition, the overall effective reflection coefficient $\boldsymbol{\rho_e}$ and the daily average of hourly cloud index $\boldsymbol{n_{avg}}$ are directly used in this model [6].

The daily average values of the hourly cloud index in equation (2) are taken so as to find daily global solar radiation. The linear correlations for selected locations show similar trends and of the form:

$$n_{avg} = d_i - c_i \frac{s}{S_o} \tag{8}$$

where $\boldsymbol{c_i}$ and $\boldsymbol{d_i}$ are the monthly correlation parameters. This relations were obtained before by Kandırmaz [7], later for a larger data set by Aksoy, Ener Rusen and Akinoglu [14] and [6]. Effective reflection $\boldsymbol{\rho_e}$ is directly related to the cloud index $\boldsymbol{n_{avg}}$ derived from satellite imagery. This relation in a simple form can be written as:

$$\rho_e = C_o + C_1 n_{avg} \tag{9}$$

The sum of the direct and diffuse component of solar irradiation can be written as in terms of four multiple regression coefficients related to $\boldsymbol{C_0}$, $\boldsymbol{C_1}$, $\boldsymbol{C_2}$ and $\boldsymbol{C_3}$. Then, the daily global solar irradiation reaching the earth, which is:

$$K = \frac{H}{H_o} = [C_1(1-n_{avg})(s/S_o)] + [C_2(1-n_{avg})(1-s/S_o)] \tag{10}$$

Using by multiple regression analysis, four dimensionless regression coefficients A_o, A_1, A_2 and A_3 for each station are obtained. Equation (10) can be re-written as:

$$K = \frac{H_{HA2}}{H_o} = A_0 + A_1 n_{avg} + A_2 \frac{s}{S_o} + A_3 \frac{s}{S_o} n_{avg} \tag{11}$$

The calculation procedure and other relevant information were explained in details by Ener Rusen, Hammer and Akinoglu [6].

III. Results and Discussion

In order to analyze the performance of the new coupled model and the known methods (Angstrom and HELIOSAT), one-year data was used for the two different climatic zones of Turkey. The database of ground level global solar irradiation and sunshine duration were obtained from Turkish State Meteorological Service (TSMS) for selected stations in Turkey. Meteosat visible channel images and all HELIOSAT calculations were carried out at University of Oldenburg. A list of the selected stations' names, their geographical locations and climatic properties in formations are presented in Table I.

TABLE I. GEOGRAPHICAL AND CLIMATIC INFORMATION OF SELECTED STATIONS

Selected Stations	Geographical Information			
	Climatic Zone	*Latitude*	*Longitude*	*Altitude (m)*
Ankara	Csa	39.97 N	32.86 E	891
Erzurum	Dsb	39.57 N	41.10 E	1758,2

Two different climate types, namely Csa (C:warm temperate, s:summer dry, a:hot summer) for Ankara and Dsb (D:snow, s:summer dry, b:warm summer) for Erzurum were determined according to the Köppen−Geiger Climate Classification [24]. The most important feature of the subtropical dry summer climates (Csa) of Ankara is dry-hot summer and cold winter seasons. Besides the temperature continental climate (Dsb) of Erzurum winters are rather cold with a durable snow cower whereas the summer season is short, however; the transition seasons are short and contain both winter and summer types. Here, the selected stations are almost the same latitudinal position but with different climate zones.

To identify the performance of this study, standard error analysis was 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 relationship was summarized with these error graphs given below in Figure 1 (A) and (B) by using a yearly relative mean bias error (rMBE) and yearly relative root mean square error (rRMSE) which are standard error analyses. For the whole period of the study, rMBE and rRMSE values are found to be smallest for Angstrom type method ($\boldsymbol{H_A}$) and the new coupled model ($\boldsymbol{H_{new}}$) which means that the estimations of Angstrom type and new coupled method are better than the satellite model ($\boldsymbol{H_{sat}}$) as expected. The relative MBE error values is about ± 0.02 and relative RMSE error values is maximum 0.18 in using $\boldsymbol{H_{new}}$. The relative error values of the new coupled model and Angstrom type method have about the same range of error values as can be observed from Figure 1. It can also be observed that new coupled model to a daily-based satellite model gives satisfactory results and is easier to utilize. In addition, Figure illustrates the comparison of the $\boldsymbol{H_{new}}$ and $\boldsymbol{H_{sat}}$

for snowy climatic characteristics of Erzurum. It is seen that the results of H_{new} estimation is lower for snowy climatic characteristics which the surface is covered by snow. This situation can be verified using snow depth and bright sunshine hours measured at snowy days for selected stations.

H_{new} is derived from bright sunshine duration and satellite derived cloud index. Due to this reason, this new coupled model should be used to estimate the daily global solar irradiation when the data of bright sunshine hours are available. It was also observed that new coupled model led to considerable improvements in the ground based estimation model.

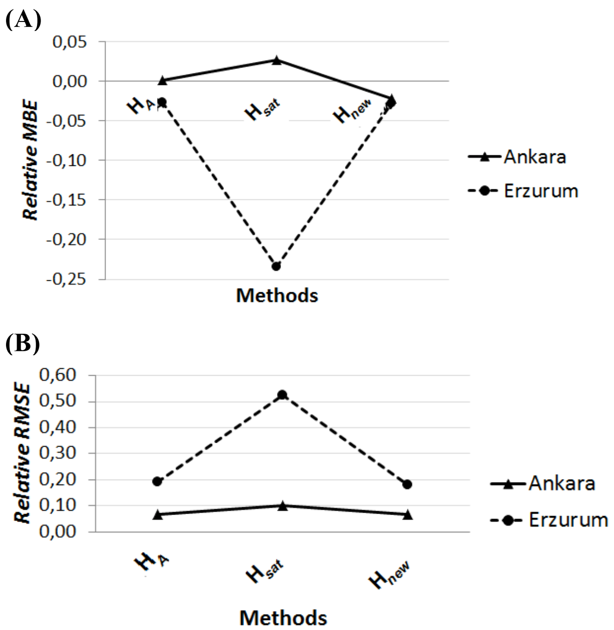

Fig. 1. (A) Yearly relative MBE and (B) yearly relative RMSE among calculated models and ground measurement of daily global solar radiation data for the two selected stations for one year. Relative values were calculated by dividing MBE and RMSE to the average of annual ground data.

IV. Conclusion

In the present study, we summarize the performance evaluation of an empirical new coupled model about the estimations of daily global solar radiation by using the satellite images and the surface data of bright sunshine hours. The analysis of the daily global solar radiation is made on the basis of the province in region of Eastern Anatolia covers the provinces of cold and snowy climatic characteristics of Erzurum and Middle Anatolia of typical continental climate characteristics of Ankara in Turkey from two different climate types, namely Dsb and Csa. The data sets were analyzed for a one-year period for the selected stations.

The original Angstrom's method, the estimations using the cloud index obtained from HELIOSAT method and a new coupled model which based on bright sunshine hours and satellite imagery are compared for the estimation of daily global solar radiation. The results are given in the error graphs in Figure 1. Compared to the relative MBE and relative RMSE values of H_{new} model are more satisfactory than the version of the other methods especially applied to the snowy climate characteristic of Erzurum. It is already expected results that the climate characteristic is quite effective parameter for the satellite based daily global solar radiation and executed a study using the data of two stations grouping them in two pairs having almost the same latitudinal position but with different climates.

Consequently, the climate change has become very important factor for our life with respect to the environmental and energy management. Also, it is known that the accurate solar radiation data provide effective information for the climate change. In order to obtain the accurate global solar radiation data can be carried out easily by using the surface data of bright sunshine hour and satellite derived cloud index with this new coupled model. The obtained results show that this new coupled model can be used in estimating the daily global solar radiation reaching the earth surface for locations having the same latitudinal position and different climate zone where reliable data is rare. Additionally, the performance evaluation results show that it can be easily extended in snow detection. The results are encouraging for the future studies to use a simple procedure about determining the days having clear sky and with snow coverage land surface into the new coupled model. However, to extend this method and to achieve an accurate algorithm, one needs large data from different stations and larger number of such specific days.

Acknowledgment

I would like to thank to Prof. Dr. Bulent Akinoglu for his discussions and comments during the course of this study. I would also like to thank State Meteorological Service (TSMS), Mr. B. Aksoy, and Carl von Ossietzky University of Oldenburg for providing us with measured data.

References

[1] R. W. Muellera, K. F. Dagestadb, P. Ineichenc, M. Schroedter-Homscheidtd, S. Crose, D. Dumortierf, R. Kuhlemanng, J. A. Olsethb, G. Piernaviejah, C. Reisei, L. Walde, and D. Heinemanng, "Rethinking satellite-based solar irradiance modelling The SOLIS clear-sky module," Remote Sens. Environ., vol. 91, pp. 160–174, 2004.

[2] A. Angström, "Solar and terrestrial radiation.," Quart. J. Roy. Met. Soc., vol. 50, pp. 121–126, 1924.

[3] P. Jes´us, Z. Luis F., and M. Lourdes Ram´ırez, "Solar Radiation Derived from Satellite Imeges," in Modelling Solar Radiation at the Earth's Surface, First., B. Viorel, Ed. Romania: Springer, 2008, pp. 449–462.

[4] H. Beyer, C. Costanzo, and D. Heinemann, "Modifications of the HELIOSAT procedure for irradiance estimates from satellite images," Sol. Energy, vol. 56, pp. 207–212, 1996.

[5] D. Cano, J. Monget, M. Albuisson, H. Guillard, N. Regas, and L. Wald, "A method for the determination of the global solar radiation from meteorological satellite data.," Sol. Energy, vol. 37, pp. 31–39, 1986.

[6] S. Ener Rusen, A. Hammer, and B. G. Akinoglu, "Estimation of daily global solar irradiation by coupling ground measurements of bright sunshine hours to satellite imagery," Energy, vol. 58, pp. 417–425, Sep. 2013.

[7] H. M. Kandirmaz, “A model for the estimation of the daily global sunshine duration from meteorological geostationary satellite data,” Int. J. Remote Sens., vol. 27, no. 22, pp. 5061–5071, Nov. 2006.

[8] M. Girodo, R. W. Mueller, and D. Heinemann, “Influence of three-dimensional cloud effects on satellite derived solar irradiance estimation—First approaches to improve the Heliosat method,” Sol. Energy, vol. 80, no. 9, pp. 1145–1159, Sep. 2006.

[9] A. Zelenka, R. Perez, R. Seals, and D. Renne, “Effective accuracy of satellite-derived hourly irradiances.,” Theor. Appl. Clim. logy, vol. 62, pp. 199–207, 1999.

[10] A. Hammer, D. Heinemann, C. Hoyer, R. Kuhlemann, E. Lorenz, R. Müller, and H. G. Beyer, “Solar energy assessment using remote sensing technologies,” Remote Sens. Environ., vol. 86, no. 3, pp. 423–432, Aug. 2003.

[11] S. E. Rusen, A. Hammer, and B. G. Akinoglu, “Coupling satellite images with surface measurements of bright sunshine hours to estimate daily solar irradiation on horizontal surface,” Renew. Energy, vol. 55, pp. 212–219, Jul. 2013.

[12] B. G. Akinoglu and S. Ener Rusen, “Combining the satellite imagery with bright sunshine hours: A review,” J. Renew. Sustain. Energy, 2013.

[13] J. A. Prescott, “Evaporation from a water surface in relation to solar radiation.,” Trans.Roy.Soc.S.A., vol. 64, pp. 114–118, 1940.

[14] B. Aksoy, S. Ener Rusen, and B. G. Akinoglu, “A simple correlation to estimate global solar irradiation on a horizontal surface using METEOSAT satellite images,” Turkish J. Eng. Env. Sci., vol. 35, pp. 125–137, 2011.

[15] J. E. Hay, “Calculation of monthly mean solar radiation for horizontal and inclined surfaces.,” Sol. Energy, vol. 23, pp. 301–307, 1979.

[16] A. Hammer, “Anwendungspezifische solarstrahlungsinformationen aus meteosat-daten.,” Carl von Ossietzky University of Oldenburg, 2000.

[17] R. Perez, R. Seals, and A. Zelenka, “Comparing satellite remote sensing and ground network measurements for the production of site/time specific irradiance data,” Sol. Energy, vol. 60, no. 2, pp. 89–96, Feb. 1997.

[18] A. Zelenka, “Using satellite data for solar energy applications,” in Heliosat-3 Workshop, 2005, no. February.

[19] J. A. Duffie and W. A. Beckman, Solar engineering of thermal processes, Third ed. New York: John Wiley and Sons, 2006.

[20] A. Hammer, D. Heinemann, E. Lorenz, and B. Luckehe, “Short-term forecasting of solar radiation: A statistical approach using satellite data,” Sol. Energy, vol. 67, pp. 139–150, 1999.

[21] B. G. Akinoglu, “Recent Advances in the Relations Between Bright Sunshine Hours and Solar Irradiation,” in Modeling solar radiation at the earth surface, V. Badescu, Ed. Verlag Berlin Heidelberg: Springer, 2008, pp. 115–143.

[22] N. M, R. CF, and F. R., “Solar irradiance estimation from geostationary satellite data: II. Physical models. Solar Energy,” Sol. Energy, vol. 51, pp. 457–465, 1993.

[23] N. M, R. CF, and F. R., “Solar irradiance estimation from geostationary satellite data: I. Statistical models,” Sol. Energy, vol. 51, pp. 449–456, 1993.

[24] M. C. Peel, B. L. Finlayson, and T. A. McMahon, “Updated world map of the Koppen-Geiger climate classification,” Hydrol. Earth Syst. Sci., vol. 11, pp. 1633–1644, 2007.