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A simple correlation to estimate global solar irradiation on a horizontal surface using METEOSAT satellite images

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Abstract

A simple quadratic correlation, which is obtained from a universal Angström-type quadratic relation, between daily horizontal global solar irradiation and satellite images is presented. The performance of this correlation is seen to be in the acceptable accuracy limits for daily estimates. In addition, by using data from 5 locations in Turkey, a linear correlation between the bright sunshine hours and satellite based cloud index is derived. Utilizing these 2 correlations, one can easily obtain spatial daily solar irradiation and sunshine duration maps for the regions with similar latitudes and climates of locations of interest.

Key Words: Bright sunshine duration; solar radiation; METEOSAT images; cloud index; Angström model

1. Introduction

There have been many studies on the estimation of solar irradiation using the surface meteorological and climatological data since the studies by Kimball (1919) and Angström (1924). Detailed discussions were presented in many articles [see, for example, Gueymard (2003), Bakırcı (2009) and Badescu (2008); such research turned out to be extremely crucial in the long- and short-term calculations of solar energy systems (Sfetsos and Conic, 2000; Bulut and Büyükalaca, 2007). Another important topic of interest might be the time series analysis, which can be used in climate change and variability investigations (Che et al., 2005; Zaharim et al., 2009). It is highly likely that such studies reveal information on the human-induced component of global warming.

The ground-based statistical models exhibit high performances. These models use one or more ground-based measurements as input parameters; the bright sunshine duration is an example. Unfortunately, the surface measuring networks have rarely been distributed the nodes of measurements, especially in the developing world. This is why the ground-based empirical models suffered a major setback. Another difficulty is that obtaining reliable surface data is hardly possible since most of these measurements are carried out using un-calibrated and/or inaccurate instruments (Akınoğlu, 1992).

Use of satellite images in estimating various solar irradiation components gave a fresh impetus to novel research on the suitable prediction models spatially and temporally (Cano et al., 1986; Zelenka et al., 1999;

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Hammer et al., 2003). To this end, the so-called physical and statistical models have been developed. Physical models try to determine solar insolation on horizontal surface by employing radiation transfer equations. The study by Gautier et al. (1980) is an important example of physical models. Statistical models, on the other hand, rely on the regression between satellite count numbers, or reflectance, and corresponding ground measurements. The empirical model proposed by Cano et al. (1986) is well known in the literature. The estimation of solar insolation on a horizontal surface by using satellite data has been the subject of many solar energy studies (Moradi et al., 2009). Satellite-based models consist of 2 steps. First, the clear sky irradiance for a given location is calculated, and then a cloud index from satellite imagery is derived. As a result, satellite-based models might have errors originating from the 2 steps. Nevertheless, such models are getting better and better in terms of accuracy and usability, though more research must be performed in order to verify the reliability of the models that utilize satellite images.

Herein, we present a study about the coupling of satellite-based estimations with empirical solar irradiation quadratic estimation models (Ögelman et al., 1984; Akınoğlu and Ecevit, 1990), which are universally validated (Tasdemiroğlu and Sever, 1989; Akınoğlu, 1991; Badescu, 1999). Using 1-year data from 5 different locations in Turkey, we have first obtained the relations between surface measurements of bright sunshine hours and cloudiness index derived from the pixel values of satellite images. We have then coupled these relations to the universally applicable quadratic correlation between the solar irradiation and bright sunshine hours (Akınoğlu and Ecevit, 1990). The obtained results are seen to be quite satisfactory; it is highly possible that further analyses with increased quantities of data from different climates will enhance the accuracy of the new approach.

2. Data, models, and methods

Satellite data depends on EUMETSAT (the European Organization for the Exploitation of Meteorological Satellites) facilities, which deliver weather and climate-related satellite data to the organization's members. The Turkish State Meteorological Service (TSMS) is also member of this organization in the name of Turkey. For this purpose, EUMETSAT has been launching meteorological satellites since 1977. METEOSAT is one of their satellites' names.

Two different data sets for 5 stations in Turkey cover the year 2004; one of them is derived from satellite images and the other is from surface measurements. The locations of the stations are shown in Figure 1; their geographical information and climate types are given in Table 1.

Table 1. List of the stations indicating their geographical locations and climate type.

Station	Latitude	Longitude	Altitude(m)	Climate (Trewartha, 1980)
Sinop	42.03S	35.15E	32	Cs/Cf
Bursa	40.23S	29.01E	100	Cs
Ankara	39.97S	32.86E	891	BS
Afyon	38.74S	30.56E	1034	BS
İzmir	38.39S	27.08E	29	Cs

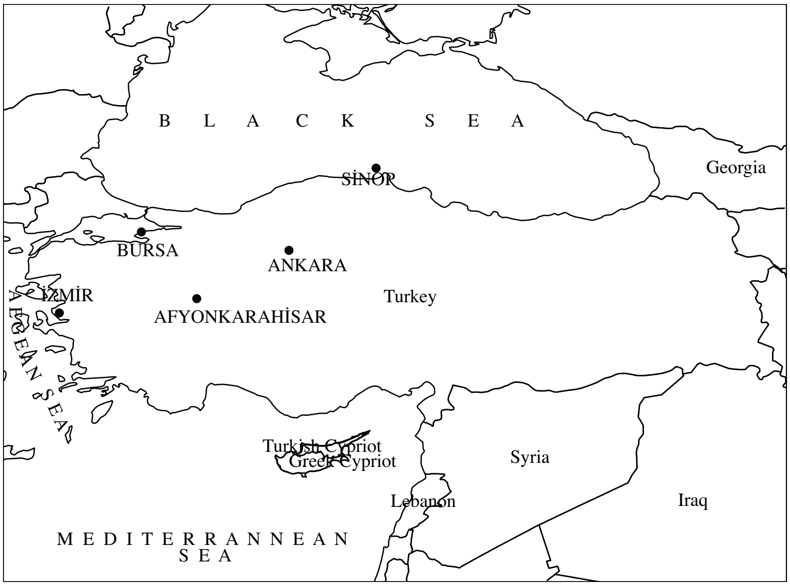

Figure 1. Spatial distribution of 5 stations in Turkey.

The images taken in the visible range of METEOSAT7 are obtained from EUMETSAT and the pixel values of locations were read using the software package METLOOK version 1.7, which is a multifunctional analysis and interpretation tool devoted to the satellite experiment of METEOSAT and can be obtained freely from the Internet. As an example a screen produced by the software METLOOK is given in Figure 2, which also covers a METEOSAT image over Turkey. Locations of the 5 sites used in this study are also shown in this figure. In order to cover sufficient local dynamic information on the atmospheric conditions of the locality (Dagestad and Olseth 2007), pixel values were read from a 3×5 matrix over the location of interest. The average of these values was used as the pixel count for that locality.

The surface data set consists of global solar irradiation and sunshine duration, which are recorded at the stations of the Turkish State Meteorological Service (TSMS). The global solar radiation and bright sunshine duration observations are taken by Fuess type actinographs and CH1-Kipp & Zonen type pyrheliometers with trackers, respectively. Pyrheliometers observe the direct beam of incoming solar radiation. On the other hand, it is possible to get the sunshine duration data using a pyrheliometer by taking into consideration a threshold value of $120\,Wm^{-2}$ for direct solar radiation. Bright sunshine duration is defined as the sum of all time periods during the day when the direct solar irradiance equals or exceeds 120 W m^{-2}. This measurement is only obtained from configurations that measure direct solar irradiance.

It is clear that the actinographs perform with rather high errors (Aksoy, 1997). Although the accuracy of actinograph data is low when compared to that taken by new generation instruments like pyranometers, they can be nonetheless used in comparisons. Another fact is that the derived model in the present work has been obtained by linking the correlations between sunshine duration and satellite images driven indices. Therefore, the irradiation data were used only for comparisons.

Angström-Prescott correlation (Angström, 1924; Prescott, 1940) between daily solar irradiation and bright sunshine hour is one of the well-known and frequently used estimation equations. Although its original form was linear, quadratic and higher order forms were also suggested; some of them have been validated by using different data from all over the world [see, for example, Ögelman et al. (1984), Akınoğlu and Ecevit

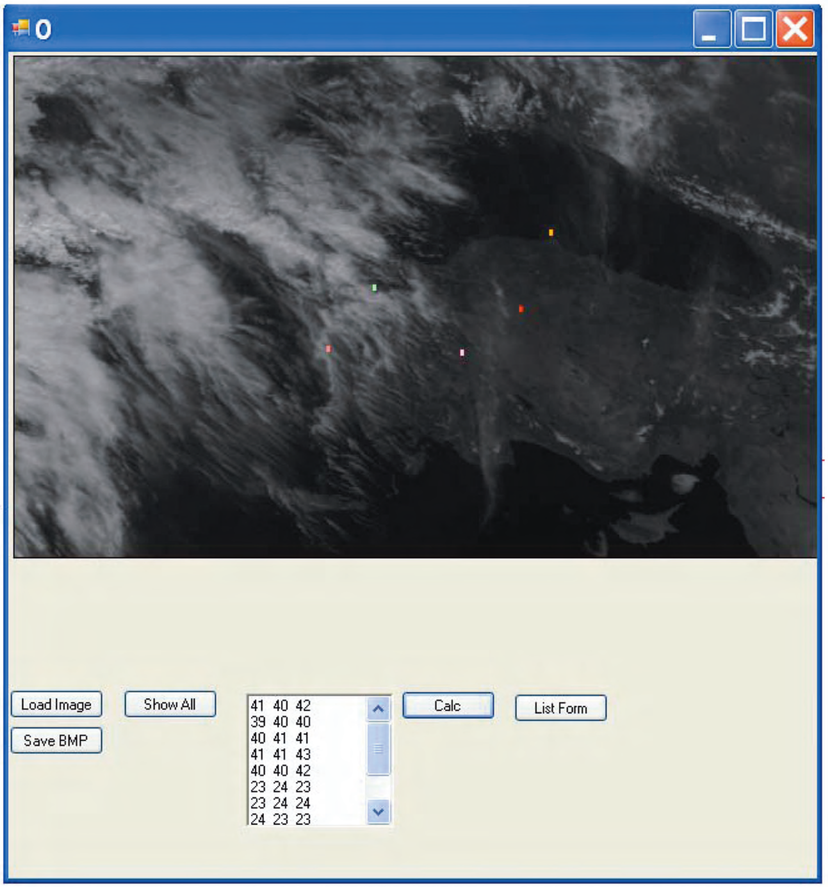

Figure 2. An example of a METEOSAT image on METLOOK screen.

(1990), Suehrcke (2000), Yang et al. (2001)].

The linear Angström-Prescott equation has the basic form

$$\frac{H}{H_0} = a + b\,\frac{s}{S}, \tag{1}$$

where H and H_0 are daily global solar irradiation and extraterrestrial daily solar irradiation on a horizontal surface, respectively, and s and S are respectively daily bright sunshine hours and the day length. The empirical constants a and b are the so-called Angström coefficients. Site dependency of these coefficients has been underlined by many researchers (Angström, 1924, 1956). Coefficient a represents an effective transmittance of overcast sky, while $a + b$ might be treated as an effective clear sky transmission for the site.

Site dependency of the Angström coefficients a and b led to a quadratic relation between them and this information has been used to construct a quadratic correlation between H/H_0 and s/S (Akınoğlu and Ecevit, 1990). In the present work, this correlation, Eq. (2), is coupled to the satellite-based empirical correlation for bright sunshine hours. The original quadratic correlation is

$$\frac{H}{H_0} = 0.145 + 0.845\,\frac{s}{S} - 0.280\left(\frac{s}{S}\right)^2. \tag{2}$$

It should be noted that this equation has been obtained solely by using the Angström coefficients a and b of 100 locations over the Earth's surface located at different climates and latitudes. No global solar irradiation measurements of any location were used, which makes this correlation a significant candidate to be applicable to all over the world when the sunshine duration data are available; its validity has been tested many times (Akınoğlu and Ecevit, 1990; Akınoğlu, 1991; Badescu, 1999). For the present work, the various correlations have also been analyzed and it has been observed that this correlation is one of the best 2 within 5 equations; therefore, we decided to use this equation in this study.

Bright sunshine duration data are readily available in many parts of the world; within their accuracy, they are quite reliable since they are measured mainly by simple Campbell-Stokes sunshine recorders (Badescu, 2008). Therefore, it seems convenient to consider the relation between the surface measurements of bright sunshine hours and cloud index derived from satellite image, which will be shortly explained below. Such a relation was first demonstrated by Olseth and Skartveit (2001), but they did not report correlation equations. Recent studies were carried out on this theme and quite satisfactory preliminary results were reported (Kandırmaz and Akınoğlu, 2005; Kandırmaz, 2006). Here, similar expressions are obtained using an extended data set containing locations from relatively different climates, and these expressions are used as the basis of coupling.

The Heliosat method was one of the early procedures for irradiance estimations, used and modified by many researchers (Gautier et al., 1980; Cano et al., 1986; Diabete et al., 1988; Beyer et al., 1996; Zelenka et al., 1999; Hammer et al., 2003; Moradi et al., 2009). Following this procedure in its simplest form, we used the daily average pixel counts C taken from a 3×5 matrix over the location of interest, which was obtained from hourly images of METEOSAT7 (http://www.eumetsat.int/Home, January 2010). Relative daily apparent albedo was then calculated by (Hammer et al., 2003)

$$\rho = \frac{(C - C_0)}{H_{\text{clear}}} \quad , \tag{3}$$

where C is the daily average of the hourly pixel counts, C_0 is a total offset resulting from an instrument, and H_{clear} is the solar irradiation for the clear sky. In the daily considerations, H_{clear} may be replaced by the daily extraterrestrial value since the clear sky values can be approximated to the daily effective clear sky transmission coefficient multiplied by extraterrestrial irradiation. In fact, with the errors that are calculated in the present study, it is also demonstrated that the use of daily H_0 values performs well within the acceptable accuracy range for the estimations of daily values.

The cloud index n, which is essentially a relative measure of atmospheric reflection of the site, can be calculated using

$$n = \frac{\rho - \rho_{\text{clear}}}{\rho_{\text{cloud}} - \rho_{\text{clear}}}, \tag{4}$$

where ρ_{clear} and ρ_{cloud} are respectively the minimum and maximum values of the daily relative apparent albedo in a month. This parameter of the site must have a significant correlation with the surface-measured bright sunshine hours since the reflection of the atmosphere also changes with cloudiness. Nevertheless, the resulting numbers span a wide range of image pixel values from overcast to clear sky conditions. As mentioned above, this idea has recently been discussed and utilized over 6 months in some locations in Turkey and encouraging results have been obtained to prepare the bright sunshine distribution map of the country (Kandırmaz and

Akınoğlu, 2005; Kandırmaz, 2006). A linear relationship can be given:

$$\frac{s}{S} = c - dn. \tag{5}$$

The outcome of this equation showed that the use of linear regression is satisfactory.

It is also possible to correlate H/H_0 and n directly as in Heliosat and all other similar methods. However, the correlation parameters will be inherently site dependent as Angström type equations between H/H_0 and s/S.

To check the site dependency of the coefficients c and d in Eq. (5), we carried out regression analyses separately for the 5 locations presented in Table 1. It has been found that the coefficients span a range of 0.70-0.80 for c and 0.74-0.97 for d. The same analyses have been carried out for the linear relation between H/H_0 and n for these cities; the slopes have been observed to vary between 1.66 and 1.38 (being negative) and the intercepts between 1.07 and 1.16.

According to the fitted variable, the quadratic correlations performed better by taking into account the variations of the deviations. Ögelman et al. (1984) applied this statistical procedure to the relation between H/H_0 and s/S and obtained satisfactory results. Hence, in the comparisons, for the estimations obtained by directly using the correlations between H/H_0 and n, we used a quadratic empirical form, which was statistically derived using a procedure proposed by Ögelman et al. (1984).

The method used in this work starts with linear regression analysis between s/S and n for 5 locations. Regressions are performed using the daily s/S values, and monthly and daily n values. The so-obtained correlations, of Eq. (5) type, are then inserted into Eq. (2) to attain universally acceptable forms for the relation between H/H_0 and n. These are then, in turn, compared with the estimations of different procedures. Detailed information on them is explained below. The abbreviations used in tables and in the text are also given:

1. We directly used the model of Akınoğlu and Ecevit (AE) (1990), namely Eq. (2).

2. For each location, the monthly relations like Eq. (5) were obtained adding up to $12 \times 5 = 60$ equations and inserted them into Eq. (2). Hence, 60 quadratic relations were obtained between H/H_0 and n. Each of these relations was then used in order to estimate the H values for the corresponding month of the same location. This procedure was called Satellite-Based Monthly (SBM) correlations. The calculations were completed using correlations obtained from the same data set. However, if the procedure is applied to 3 of the locations together by taking into account all data of each month, then totally 12 equations can be obtained. These equations then can be used for the irradiation estimations of the other 2 locations by using their n values. This can reveal some information on the applicability of the procedure. We carried out such a procedure for the locations Sinop, Ankara, and İzmir, and then used it in order to estimate the daily solar irradiation values for Bursa and Afyon. This procedure was called SBM1.

3. Only one linear relation between s/S and n was obtained using all the daily data of all the locations:

$$\frac{s}{S} = 0.8181 - 0.8496n. \tag{6}$$

This relation was inserted into Eq. (2) and the quadratic correlation that we consider to be universally applicable was obtained as

$$\frac{H}{H_0} = 0.649 - 0.329n - 0.202n^2. \tag{7}$$

This method was called the Satellite Based Quadratic (SBQ) relation. For testing the performance of this procedure, similar to above, the analysis for 3 locations, namely Sinop, Ankara, and İzmir, was carried out, and then the obtained quadratic expression was used for the estimations of solar irradiation of the other 2 locations (Bursa and Afyon). The abbreviation SBQ1 represents this theme.

4. Additional calculations were performed using the monthly average daily values. The followed procedure is the same as above. The linear correlation

$$\frac{s}{S} = 1.0167 - 1.4614n \tag{8}$$

was obtained and inserted into Eq. (2), giving the expression

$$\frac{H}{H_0} = 0.715 - 0.403n - 0.598n^2 \tag{9}$$

We called this expression the Satellite Based Monthly Quadratic (SBMQ) relation.

5. Finally, the estimations for the comparisons were done using a directly derived quadratic relation by regression analysis between H/H_0 and n. The expression was obtained as

$$\frac{H}{H_0} = 0.773 - 0.698n + 0.132n^2. \tag{10}$$

This expression was called the Satellite Based Direct Quadratic (SBDQ). Equation (10) has also been used in the comparisons but it essentially gives information about the quality or excellence of the fit. Because the same data were used in operations, they have been utilized for comparison, as in the second method above. To test the performance, a similar procedure has been applied to 3 locations, and the resulting correlation ($H/H_0 = 0.655 - 0.329\,n - 0.213\,n^2$) is used for the comparison by using the data of the other 2 locations (SBDQ1).

The accuracy of relations was tested by calculating the differences (BE), the root mean square error ($RMSE$), the mean bias (MBE), the relative error (RE), and the t-statistic errors as follows:

$$BE = H_{\mathrm{ic}} - H_{\mathrm{im}} \tag{11}$$

$$MBE = \left[\sum_{i=1}^{n} BE\right] / n \tag{12}$$

$$RMSE = \left\{\left[\sum_{i=1}^{n} (BE)^2\right] / n\right\}^{1/2} \tag{13}$$

$$RE = \frac{BE \times 100}{\langle H \rangle} \tag{14}$$

$$t_{statistic} = \left[(P-1)MBE^2/(RMSE^2 - MBE^2)\right]^{1/2} \tag{15}$$

On the other hand, Pearson's correlation coefficient [Eq. (16)] was used in order to detect the nature and magnitude of relationship between observed and estimated solar data sets. The statistical significance of correlation coefficients was checked at the 0.05 significance level by using the 2-tailed test of Student's t distribution [Eq. (17)]; the null hypothesis of "absence of any relationship between observed and estimated series" is rejected for large values of $|t|$ with (N-2) degrees of freedom. The term 'significant' used in present paper without a specification for a level of significance is at the 0.05 level. Moreover, the critical value of t for all significance performances is taken as 2.23.

$$r_{xy} = \frac{N\sum x_i y_i - \sum x_i y_i}{\sqrt{N\sum x_i^2 - (\sum x_i)^2}.\sqrt{N\sum y_i^2 - (\sum y_i)^2}} \tag{16}$$

$$t = r_{xy}\sqrt{\frac{N-2}{1-r^2}} \tag{17}$$

3. Results and discussion

The correlation coefficients are computed as 0.81 and 0.82 for the relations between H/H_0 and n, and s/S and n, respectively. It was detected that these 2 correlations are significant. Figures 3 and 4 are the graphs of H/H_0 and n, and s/S and n, respectively, which have been produced using all daily data of the 5 locations. In Figure 3, we have also inserted Eq. (7), from which one can roughly observe the agreement between the data points and the curvature of the line. It should be noted that for $n = 1$ there are quite wide spans for H/H_0 and s/S values. This is the result of the higher relative albedo in the winter months both for relatively clear days with snow coverage and for the days with overcast skies. Therefore, one may introduce the surface information in order to enhance the performance of these correlations.

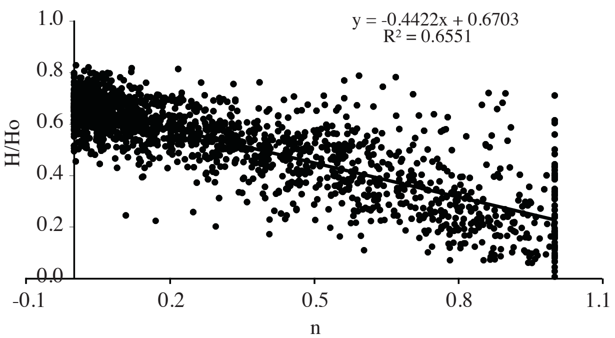

Figure 3. Scatter diagram of the daily normalized global solar radiation with the extraterrestrial radiation (H/H_0) and cloud index (n) for 5 meteorological stations in Turkey.

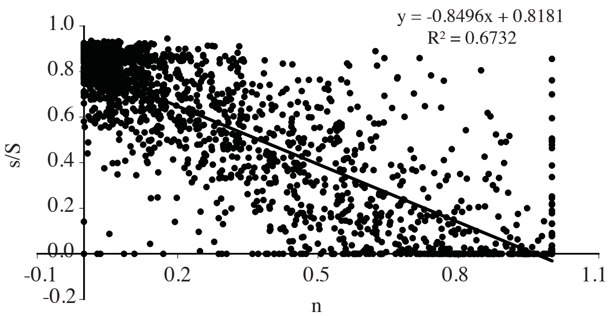

Figure 4. Scatter diagram of the daily normalized bright sunshine duration with the day-length (s/S) and cloud index (n) for 5 meteorological stations in Turkey.

The correlation coefficients between estimated and observed data series were also computed and given in Table 2. According to Eq. (17), it has been found that all of them are significant statistically. The value of t-statistic for the outputs of Eq. (7) is acceptable: 2.29. This may also suggest that such a direct use of n in estimating H is noteworthy. Table 2 summarizes the results of comparisons of the 8 outlined procedures.

Table 2. Correlation coefficient (r), root mean square error (RMSE), mean bias error (MBE), t-statistic, bias analyses, and relative error (RE) of proposed models according to the ground observed data. The units of RMSE, bias, and MBE are in MJ m^{-2} and RE in percent.

Model	Test	Afyon	Ankara	Bursa	İzmir	Sinop	All Stations
AE	r	0.99	1.0	1.0	1.0	1.0	1.0
	RMSE	1.34	1.20	0.86	1.32	0,49	1.08
	MBE	-0.61	0.65	-0.00	-1.25	-0.19	-0.27
	t-statistic	1.54	2.12	0.00	9.14	1.38	1.92
	RE	10.13	6.35	6.29	7.64	3.86	6.74
	Max. Bias	-2.65	2.34	1.58	-2.65	-1.85	-2.65
	Mean Bias	1.09	0.98	0.71	1.09	1.25	0.88
SBM	r	0.99	1.0	1.0	1.0	1.0	1.0
	RMSE	1.34	1.20	0.86	1.32	0,49	1.08
	MBE	-0.61	0.65	0.00	-1.25	-0.19	-0.27
	t-statistic	1.54	2.12	0.00	9.14	1.34	1.92
	RE	10.13	6.35	6.30	7.64	3.79	6.73
	Max. Bias	-2.65	2.34	1.58	-1.86	-1.04	-2.65
	Mean Bias	1.09	0.98	0.71	1.25	0.41	0.88
SBQ	r	0.99	0.99	0.99	0.99	0.99	0.99
	RMSE	1.74	0.83	1.22	2.79	1.11	1.68
	MBE	-1.17	-0.09	0.51	-2.18	0.49	-.049
	t-statistic	2.72	0.37	1.51	4.15	1.65	2.29
	RE	9.82	6.02	9.21	11.38	8.26	8.91
	Max. Bias	-3.66	-2.11	-2.62	-6.12	-2.36	-6.12
	Mean Bias	1.46	0.62	0.97	2.28	0.89	1.24
SBMQ	r	0.97	0.99	0.99	0.99	0.98	0.97
	RMSE	2.20	0.91	1.32	2.10	1.37	1.63
	MBE	-1.41	0.06	0.71	-1.57	0.27	-0.37
	t-statistic	2.77	0.22	2.09	3.73	0.67	1.74
	RE	13.61	5.92	9.28	8.12	7.85	8.80
	Max. Bias	-4.48	-1.55	2.99	-5.34	-3.11	-5.34
	Mean Bias	1.72	0.77	1.16	1.59	1.09	1.25
SBDQ	r	0.98	0.99	0.99	0.99	0.99	0.98
	RMSE	1.25	1.50	2.10	1.42	1.97	1.69
	MBE	0.16	1.24	1.86	-0.59	1.61	0.84
	t-statistic	0.38	4.48	5.72	1.51	4.28	4.31
	RE	7.72	10.96	16.38	5.83	15.02	11.30
	Max. Bias	-2.77	2.52	4.03	-4.08	3.43	-4.08
	Mean Bias	1.01	1.35	1.90	0.98	1.78	1.42
SBM1	r	0.99	0.99	0.99	0.99	0.99	0.98
	RMSE	1.28	1.00	1.40	1.97	1.43	1.46
	MBE	-0.66	0.26	0.87	-1.84	0.91	-0.07
	t-statistic	1.99	0.90	2.65	8.74	2.74	0.37
	RE	8.78	5.75	6.80	11.07	7.15	7.88
	Max. Bias	2.54	2.15	3.68	3.28	2.99	3.68
	Mean Bias	0.98	0.82	0.97	1.84	1.04	1.13

Table 2. Contunied.

Model	Test	Afyon	Ankara	Bursa	İzmir	Sinop	All Stations
SBQ1	r	0.97	0.99	0.99	0.99	0.98	0.97
	RMSE	2.24	0.99	1.42	1.98	1.45	1.65
	MBE	-1.36	0.15	0.80	-1.43	0.32	-0.28
	t-statistic	2.55	0.51	2.26	3.47	0.75	1.31
	RE	14.05	6.59	10.12	7.53	8.58	9.21
	Max. Bias	4.50	1.57	3.22	5.14	3.09	5.14
	Mean Bias	1.76	0.85	1.26	1.45	1.17	1.28
SBDQ1	r	0.99	0.99	0.99	0.99	0.99	0.98
	RMSE	1.62	0.79	1.26	2.63	1.17	1.62
	MBE	-1.02	0.06	0.66	-2.02	0.63	0.34
	t-statistic	2.67	0.24	2.01	3.95	2.14	1.62
	RE	9.16	5.90	9.94	10.81	9.12	8.98
	Max. Bias	3.53	1.95	2.38	5.89	2.15	5.89
	Mean Bias	1.34	0.56	1.05	2.15	0.99	1.21

Note that the error values presented in this table were obtained using measured daily surface data via Eqs. (11)-(15) given above. Comparison of the methods SBQ and SBMQ with the estimations of the methods of AE and SBDQ together with SBDQ1 shows that presented procedure can be used within acceptable accuracies, as shown in Table 2. That is, Eq. (7) can be used for the estimations of daily solar irradiation on a horizontal surface via only the satellite images, with comparable errors, obtained using surface based bright sunshine hours by the Angström type models.

If one compares SBQ and SBQ1, even for the set of parameters derived from the data of different locations, the new approach responds well, indicating the possibility of proposing its universal applicability. Another noteworthy conclusion can be reached by comparing the results of SBQ with those of SBDQ and SBDQ1. When the model developed by inserting the empirical relation between surface bright sunshine hours and satellite images [Eq. (6)] into the equation derived by Akınoğlu and Ecevit (1990) [Eq. (2)], namely the method SBQ [Eq. (7)], the responses are even better than the correlation constructed directly between H/H_0 and n, namely SBDQ and SBDQ1. Of course, further research is needed using data from all over the world to test the applicability of Eq. (7).

Another result to discuss is the use of either daily or monthly average values in the construction. Since SBQ seems better than SBMQ, the construction of the model by using monthly averages did not result in an enhancement of the performance, which was rather unexpected. This is probably due to the loss of daily connections between both H/H_0 and s/S, and s/S and n upon averaging them.

Last but not least is the comparison of AE with SBM. As can be observed readily, both approaches give exactly the same error values. This is reasonable since we used in SBM a different correlation for each month, derived by inserting the monthly regressions, i.e. Eq. (5) into Eq. (2). This result also confirms that, via the present approach, the applicability of Eq. (2) (AE) is transferred to the new correlations between H/H_0 and n successfully. However, since the use of monthly quadratic forms is rather cumbersome, a single quadratic H/H_0 and n expression obtained via Eq. (5) and Eq. (2), namely Eq. (7), can also attain high performances in the estimations, as demonstrated above.

One of the important steps in the use of the pixel readings of satellite imagery is the normalization of these values with a suitable clear day value of the site, H_{clear}. In fact, instead of H_{clear} one can also use daily H_0 values since our preliminary analysis in the present work revealed that the estimations are within the acceptable accuracy limits, as seen in Table 2. The apparent albedo can then be calculated directly from the daily averages of the pixel counts, and so are daily values of n. Inserting n into Eq. (7) gives daily H/H_0 values of the location of interest on the surface of the Earth where the satellite images exist. Hence, it should be underlined that use of daily H_0 values for normalizing the daily average pixel counts gives acceptable estimates of daily solar radiation. The suggestion is the possibility of using the present correlation for daily estimates over any points on the surface of the earth where no surface measured data exist.

It is also possible to find monthly a and b values for a specific region, if at least 1 year reliable bright sunshine hours and global solar irradiation data exist for a location close to the region of interest. Use of the monthly a and b values of this location within the region of interest in connection with satellite-based models, in principle, should give better spatially continuous estimates of daily (or monthly) global solar irradiation on a horizontal surface, simply by using the pixel counts of satellite images of the regions in the vicinity of that locality.

4. Conclusion

The present work summarizes a simple derivation of a correlation between the daily horizontal global irradiation and satellite-based relative apparent albedo. It is demonstrated that direct and simple use of the daily cloud index derived from satellite images can achieve estimates of the daily horizontal global solar irradiation on the surface of the Earth with acceptable accuracies. The correlation is derived by inserting the relation between the sunshine duration and the satellite-based cloud index into a universal Angström type quadratic model between the sunshine duration and daily horizontal global irradiation. We suggest the use of Eq. (7) for this. We should also note once more that Eq. (7) is derived using the regression between bright sunshine hours and data from satellite images, and inserting it into Eq. (2). In fact, since Eq. (2) was derived directly from a and b values of 100 locations, it is interesting to note that in deriving Eq. (7) we did not use at all any measured solar irradiation data on the Earth's surface.

Another important outcome of this work is a new linear relation between sunshine duration and relative cloud index derived from the satellite images, namely Eq. (6). This relation was first demonstrated by Olseth and Skartveit (2001) and the correlation was first obtained for only a 6-month period for some locations (Kandırmaz, 2006). The new linear relation covers all the months from 5 locations in Turkey between the latitudes 38.4°N and 42.3°N. Therefore, we suggest using Eq. (6) to determine a spatial map of daily sunshine duration using satellite images, for the locations having close latitudes and climates considered in the present.

The correlations presented can be modified using a larger data set spanning wider ranges of latitude and climate. It is also possible to extend this work and obtain different sets of equations by dividing the regions into coastal, inland, and high-altitude and/or by monthly-based applications so that better estimates can be attained. Use of the images of the Meteosat Second Generation satellite (MSG) can increase the accuracy.

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