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Estimation of solar radiation from cloud cover data of Bangladesh

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Abstract

In this study, an analysis of the monthly mean values of the fraction of the sky covered by clouds (*C*) of all types and the duration of bright sunshine hours (*S*) and global solar radiation on the horizontal surface (*H*) was carried out to establish relationship for solar radiation estimation for Bangladesh. The relationship between *C* and $(1 - S/S_0)$, where S_0 is the maximum possible hours of sunshine, was found to be nonlinear. The relationship between *C* and $(1 - H/H_0)$, where H_0 is the extraterrestrial solar radiation, was also found to be nonlinear. Few quadratic regression equations were derived for different regions of Bangladesh. The data were separated in Zone 1 (below the tropic of cancer, i.e., ≤23.5°N) and Zone 2 (above the tropic of cancer, i.e., ≥23.5°N). All the developed models were checked statistically. It was found that it is always better to estimate solar radiation from sunshine duration as it gives the best estimation and accuracy, but if there is no sunshine duration data available for a site, then solar radiation can be estimated directly from cloud cover data. Estimating sunshine duration first from cloud data to estimate solar radiation introduces more error as it has to go through the modeling stage twice. In case of the need of sunshine duration data only, the estimation from cloud cover is quite helpful. It was also found from the study that for small country like Bangladesh separating data according to latitude has insignificant effect.

Keywords: Sunshine duration, Cloud cover, Global solar radiation estimation, Correlation models

Background

Bangladesh is a small south Asian country with an area of 147,570 km^2 and located between latitudes 20.59°–26.63°N and longitudes 88.01°–92.67°E. Among fossil fuel, Bangladesh has only natural gas that is used in power generation in the country (Ahiduzzaman and Islam 2011). According to Bangladesh Power Development Board (BPDB), Bangladesh has a total installed capacity of 11,532 MW, and among them 62.76 % of the total generation comes from natural gas (Bangladesh Power Development Board 2015). A large amount of imported furnace oil is burnt to produce 20.45 % of total power which emits a huge amount of CO_2 and other toxic gases. The estimated reserve of natural gas which is around 13.75 Tcf would meet the country's demand till 2015. After that, there will be a shortage of gas supply which would rise to 4421 MMcfd by 2025. Therefore, an additional 8.35 Tcf supply of gas is to be met by some other means (Ahiduzzaman and Islam 2011). Fortunately, Bangladesh receives moderate amount of daily sunshine of 4.5–4.8 kWh/m^2 which can be proved very significant for a sustainable power sector (Mondal and Islam 2011).

Knowledge of the amount of global solar radiation of an area is essential to design various solar energy systems. Unfortunately, solar radiation measurement instruments are costly and require proper maintenance and calibration. Therefore, solar radiation data are not readily available to the designers of solar energy systems, decision makers, or the investors. Being a developing country, Bangladesh has very less investment in technology to measure solar radiation all over the country. In fact, there is no solar radiation measurement instrument installed in any station of Bangladesh Meteorological Department (BMD 2015). So there is a need to develop methods for estimating solar radiation from other meteorological parameters like sunshine hour data or cloud cover data.

In past, many empirical models were developed by many researchers using various meteorological parameters like sunshine hours (Angstrom 1924), precipitation

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(Hargreaves and Samani 1982), air temperature (Jong and Stewart 1993), relative humidity (Elagib et al. 1998), and cloudiness (Black 1956) to establish a relationship with solar radiation. Bakirci (2015) has developed some new empirical models for predicting the monthly mean diffuse solar radiation on a horizontal surface for typical cities in Turkey. Chelbi et al. (2015) have done the solar radiation mapping using sunshine duration-based models and interpolation techniques for Tunisia. Simple correlation for estimating the global solar radiation on horizontal surfaces for India was done by Katiyar and Pandey (2010). Liu et al. (2015) found the changes in the relationship between solar radiation and sunshine duration in large cities of China. Robaa (2008) has done the evaluation of sunshine duration from cloud data in Egypt. Yang et al. (2012) have done the hourly solar irradiance time-series forecasting using cloud cover index. Nimnuan and Janjai (2012) have found another approach for estimating average daily global solar radiation from cloud cover in Thailand. New types of simple nonlinear models to compute solar global irradiance from cloud cover amount were found by Badescu and Dumitrescu (2014). Ehnberg and Bollen (2005) have done a simulation of global solar radiation based on cloud observations. Reddy (1974) has developed an empirical method for estimating sunshine from total cloud amount. Morf (2014) has done sunshine and cloud cover predictions based on Markov processes. Babatunde and Aro (1995) have established a relationship between "clearness index" and "cloudiness index" at a tropical station, for instance, Ilorin, Nigeria. Al-Mostafa et al. (2014) have done a review of sunshine-based global radiation models. Manzano et al. (2015) established a method to estimate the daily global solar radiation from monthly data.

However, most of the models used sunshine duration to estimate solar radiation (Al-Mostafa et al. 2014). The most widely used and accepted method is that of Angstrom (1924) who proposed a linear relationship between the ratio of average daily global radiation to the corresponding value on a clear day and the ratio of average daily sunshine duration to the maximum possible sunshine duration.

Although there are 35 sunshine duration measurement stations of BMD installed in different areas of Bangladesh, there are still too few of them to cover the whole country. Therefore, it is essential to estimate solar radiation from other climatological parameters like cloud cover. In fact, cloud cover data are more numerous and in some instances geographically better distributed than sunshine hour data (Iqbal 1983).

Furthermore, there is no publication or previous study on the prediction of solar radiation from cloud cover data of Bangladesh. Therefore, the main objective of this study is to establish simple models to estimate solar radiation from cloud cover precisely. This is done by two different ways: First, quadratic models were developed for different regions of Bangladesh to estimate sunshine duration from cloud cover data, and then using models already established by other researchers (Al-Mostafa et al. 2014; Chelbi et al. 2015; Li et al. 2011; Ampratwum and Dorvlo 1990; Sen 2007) solar radiation was estimated. Second, regression models are developed to estimate solar radiation directly from cloud cover data. Later on, the results of these two different ways are compared by statistical error tests.

The climate of Bangladesh

Bangladesh is a small south Asian country which has an area of 147,570 km^2 and located between latitudes 20.59°–26.63°N and longitudes 88.01°–92.67°E. It is a low-lying plain situated on deltas of large rivers flowing from the Himalayas. The climate of Bangladesh is a subtropical climate with high seasonal variations in rainfall, moderately warm temperatures, and high humidity (Rashid 2006). There are four distinct seasons: (1) the dray winter season from December to February, (2) the pre-monsoon hot summer season from March to May, (3) the rainy monsoon season from June to September, and (4) the post-monsoon autumn season which lasts from October to November (Shahid 2010). Because of these distinct seasons, Bangladesh receives variable rainfall according to place and time. Rainfall varies from 1400 to 4400 mm from west to east, respectively. The rainfall gradient is 7 mm/km from west to east of the country (Shahid 2010). More than 75 % of the total rainfall occurs during the monsoon. Therefore, in terms of cloud coverage, we can expect clear days (0–2 oktas) in the dry winter season (from December to February), mixed days (2–4 oktas) in both pre- and post-monsoon seasons (from March to May and from October to November, respectively), and overcast days (4–8 oktas) in the rainy monsoon season (from June to September) (Khadem et al. 2007). During winter, the average temperature of the country ranges from 7.2 to 12.8 °C and during summer 23.9–31.1 °C (Shahid 2010). The coldest month is January and the hottest month is May in Bangladesh. In winter, there are also foggy and misty days from December to January which might also restrict solar insolation to reach the surface.

Methods

Estimation of sunshine duration from cloud amount

From ancient time, people knew the relationship between sunshine and cloud cover. Early researchers also knew that there is an inverse relationship between insolation and the amount of sky covered by clouds (Kimball 1919).

The inverse relationship results from the fact that sunshine duration (S) records are usually caused by the sun being obstructed by cloud cover (C) of sufficient opacity (Rangarajan et al. 1984). The relationship between mean cloudiness C and the global solar radiation H is given by the well-known Angstrom–Savinov formula (Rangarajan et al. 1984) as:

$$H = H_0[1 - (1 - k)C] \tag{1}$$

where H_0 is the estimated daily global radiation for a cloudless sky, C is the monthly average fraction of the daytime sky obscured by clouds, and k is a constant defining the transmission of solar radiation within the clouds. Generally, the value of k varies between 0.55 in high latitudes and 0.33 in low latitudes (Mani et al. 1967). This formula is very similar to the Anstrom–Prescott (A–P) formula relating sunshine duration (S) with global solar radiation (H) as:

$$H = H_0\left[a + b\left(\frac{S}{S_0}\right)\right] \tag{2}$$

where N is the maximum possible duration of bright sunshine during the day and a and b are regression coefficients to be found. According to Rangarajan et al. (1984), if the estimate is correct and free from visual errors, then the total cloud amount should follow the relationship as:

$$C = (1 - S/S_0) \tag{3}$$

If Eq. (3) is valid, then all points should lie clustered along the straight line passing through the origin and the (1, 1) point. Unfortunately, cloud cover estimation is not free from error. Rather it depends on the perspective of the viewer. In some extreme cases, it is possible that a small hole in the cloud could remain open for a long period of time or one small cloud could keep the sun obscured for a long time while moving with the sun (Iqbal 1983). The reflection of solar radiation from the edges could also increase the insolation enough to burn the card of Campbell–Stokes sunshine recorder. So the plot of Eq. (3) will not coincide with $y = x$ line. Rather it will deviate from ideal conditions. Therefore, a correlation is necessarily to be found to estimate sunshine duration. In this study, we have established correlations between cloud cover with sunshine hour for different stations of Bangladesh.

Using the correlations found from (3), we can estimate S/S_0. Then, multiplying this value with S_0 will provide us the value of S.

Estimation of solar radiation from estimated sunshine duration

We can use the estimated sunshine duration data as described in the previous section to further estimate the solar radiation of the region. Different regression models to estimate global solar radiation on the horizontal surface from sunshine duration which are proposed in the literature are given in Table 1 (Almorox and Hontoria 2004; Angstrom 1924; Prescott 1940; Akinoglu and Ecevit 1990; Ertekin and Yaldiz 2000; Ampratwum and Dorvlo 1990; Sen 2007). The models that can be used to estimate solar radiation from sunshine duration for Bangladesh are given in Table 2. We have used the general Angstrom–Prescott type model to estimate solar radiation from sunshine duration estimated previously from cloud cover data.

In the models in Table 1, H is the global solar radiation on horizontal surface (kWh/m^2), H_0 is the extraterrestrial radiation (kWh/m^2), S is the sunshine duration (h), S_0 is the day length (h), and a, b, c, and d are the empirical coefficients.

Extraterrestrial solar radiation H_0 can be calculated according to Duffie and Beckman (2006):

$$H_0 = \frac{(24 \times 3600 G_{sc})}{\pi}\left(1 + 0.033\cos\frac{360D}{365}\right) \times (\cos\phi\cos\delta\sin\omega_s) + \frac{(\pi\omega_s)}{180}\sin\phi\sin\delta \tag{4}$$

where G_{sc} is the solar constant (1367 W/m^2), D is the day number of the year counting from first January, ϕ is the latitude of the place (°), ω_s is the sunset hour angle (°), and δ is the solar declination (°).

Table 1 Empirical models to calculate solar radiation from sunshine duration

Models	Regression equations	Source
Linear	$H/H_0 = a + b(S/S_0)$	Angstrom–Prescott (1924, 1940)
Quadratic	$H/H_0 = a + b(S/S_0) + c(S/S_0)^2$	Akinoglu and Ecevit (1990)
Third degree	$H/H_0 = a + b(S/S_0) + c(S/S_0)^2 + d(S/S_0)^3$	Ertekin and Yaldiz (2000)
Logarithmic	$H/H_0 = a + b \cdot \log(S/S_0)$	Ampratwum and Dorvlo (1990)
Exponential	$H/H_0 = a \cdot \exp[b \cdot (S/S_0)]$	Almorox and Hontoria (2004)
Power	$H/H_0 = a \cdot (S/S_0)^b$	Sen (2007)

Table 2 Regression equations to estimate solar radiation from sunshine duration for Bangladesh

#	Annual models	Equations	R^2
1	Linear	$H/H_0 = 0.4256(S/S_0) + 0.2199$	0.8888
2	Quad.	$H/H_0 = 0.749(S/S_0)^2 - 0.3752(S/S_0) + 0.417$	0.8920
3	Cubic	$H/H_0 = 3.1987(S/S_0)^3 - 4.4223(S/S_0)^2 + 2.3158(S/S_0) - 0.0306$	0.8899
4	Expo.	$H/H_0 = 0.2673\exp[0.9422(S/S_0)]$	0.8913
5	Log.	$H/H_0 = 0.2152\ln(S/S_0) + 0.5916$	0.8729
6	Power	$H/H_0 = 0.6093(S/S_0)^{0.478}$	0.8804

The value of δ and ω_s can be calculated from Eqs. (5) and (6), respectively (Duffie and Beckman 2006):

$$\delta = 23.45\sin\left[\frac{360(D+284)}{365}\right] \tag{5}$$

$$\omega_s = \arccos[-\tan(\delta)\tan(\phi)] \tag{6}$$

The day length S_0 can be calculated using the value of ω_s as follows (Duffie and Beckman 2006):

$$S_0 = \frac{2}{15}\omega_s \tag{7}$$

Now, the ratio H/H_0 can be found by substituting the values of measured global solar radiation (H) and extra-terrestrial radiation H_0. This ratio H/H_0 is known as clearness index which gives the percentage deflection by the sky of the incoming global radiation and changes in the atmospheric conditions in a given locality (Iqbal 1983).

Estimation of solar radiation directly from cloud cover data

In 1956, Black used data of 88 stations from all over the world to develop an empirical relationship between solar radiation and cloud cover (Black 1956). He used the mean monthly values for 88 stations and performed a regression analysis to find the following relationship between H/H_0 and C:

$$\frac{H}{H_0} = 0.803 - 0.340C - 0.458C^2 \tag{8}$$

Unfortunately, this relationship can produce substantial amount of error as according to Black himself (Black 1956): (1) Mean monthly values were calculated from the maximum numbers of years and (2) different instruments have been used in different stations and no attempts have been made to reduce these instruments to a common standard.

Therefore, we have done a regression analysis to establish some new models to estimate solar radiation (H) directly from cloud fraction (C) for Bangladesh. To do this, we have established a relationship between clearness index, H/H_0, and cloud fraction, C. The value of H/H_0 can be determined similarly as shown in section "Estimation of solar radiation from estimated sunshine duration."

Data

In this work, the measured daily global solar radiation data are taken from Institute of Energy (previously known as Renewable Energy Research Center), University of Dhaka and Bangladesh Meteorological Department (BMD). Measured time-series data of global solar radiation were available for five sites, and sunshine duration and cloud cover data were available for 34 stations of BMD.

Institute of Energy (RERC) measured global solar radiation from January 2003 to December 2005 using two Eppley PSP Pyranometers at 1-min interval for 24 h. In BMD, sunshine duration data were recorded using Campbell–Stokes sunshine recorders. Cloud cover data were also taken from ground observations at 1-h interval by estimating the total fraction of the celestial dome covered by clouds of any thickness and then rounded to the nearest one-eighth, or okta. The data are divided into two zones for better estimation. The data of Zone 1 come from stations having latitude less than those of Tropic of Cancer (23.5°N), and the second zone is formed with stations having latitude greater than Tropic of Cancer (23.5°N). This is done to check the effect of latitude on the regression equations as well as to find a more accurate estimation. Table 3 shows detailed information about the stations and their period of observation of meteorological data, and Fig. 1 shows the geographical distribution of BMD stations over Bangladesh.

German Aerospace Center (DLR) time-series data (German Aerospace Center 2015) of global solar radiation was also available for ten sites from Solar and Wind Energy Resource Assessment (SWERA) project database (Schillings et al. 2014). The DLR data were not used to find model parameters; rather it was used to have an assumption of the validity of the models.

Table 3 Geographical locations and period of data of the BMD stations

Station name	WMO station no.	LAT. (°N)	LONG. (°E)	Elev. (m)	Period of observations		
					Global solar radiation	Sunshine duration	Cloud cover
Zone 1							
Teknaf	41998	20.87	92.26	4	–	1977–2013	1977–2013
Cox's Bazar	41992	21.46	91.98	4	–	1961–2013	1948–2013
Kutubdia	41989	21.83	91.84	6	–	1984–2013	1985–2013
Khepupara	41984	21.98	90.22	3	–	1988–2013	1974–2013
Hatiya	41963	22.29	91.13	4	–	1985–2013	1966–2013
Chittagong	41978	22.34	91.79	6	–	1961–2013	1949–2013
Patuakhali	41960	22.36	90.34	3	–	1985–2013	1973–2013
Mongla	41958	22.43	89.66	4	–	2001–2013	1991–2013
Sandwip	41964	22.5	91.46	6	–	1987–2013	1967–2013
Sitakunda	41965	22.64	91.64	4	–	1977–2013	1977–2013
Rangamati	41966	22.67	92.2	63	2005	1987–2013	1957–2013
Satkhira	41946	22.68	89.07	6	2005	1984–2013	1948–2013
Barisal	41950	22.7	90.36	4	–	1967–2013	1949–2013
Bhola	41951	22.7	90.66	5	–	1981–2013	1966–2013
Khulna	41947	22.8	89.58	4	–	1984–2013	1948–2013
Maijdee Court	41953	22.83	91.08	6	–	1985–2013	1951–2013
Feni	41943	23.01	91.37	8	–	1985–2013	1973–2013
Madaripur	41939	23.17	90.18	5	–	1988–2013	1977–2013
Jessore	41936	23.17	89.22	7	–	1967–2013	1948–2013
Chandpur	41941	23.26	90.67	7	–	1977–2013	1964–2013
Comilla	41933	23.48	91.19	10	–	1981–2013	1948–2013
Zone 2							
Faridpur	41929	23.61	89.84	9	–	1985–2013	1948–2013
Chuadanga	41926	23.65	88.82	0	2005	2003–2013	2001–2013
Dhaka	41923	23.78	90.39	9	2003–2005	1961–2013	1953–2013
Ishurdi	41907	24.12	89.04	14	–	1985–2013	1961–2013
Tangail	41909	24.15	89.55	10	–	1987–2013	1987–2013
Srimangal	41915	24.29	91.73	23	–	1986–2013	1948–2013
Rajshahi	41895	24.35	88.56	20	–	1979–2013	1964–2013
Mymensingh	41886	24.75	90.41	19	–	1979–2013	1948–2013
Sylhet	41891	24.88	91.93	35	–	1962–2013	1956–2013
Bogra	41883	24.88	89.36	20	2005	1961–2013	1948–2013
Dinajpur	41863	25.63	88.66	37	–	1989–2013	1948–2013
Rangpur	41859	25.72	89.26	34	–	1979–2013	1954–2013
Syedpur	41858	25.75	88.92	0	–	2003–2013	1991–2013

Statistical evaluation

To evaluate different models developed in this study, six statistical quantitative indicators were used. These quantitative indicators are: the coefficient of determination (R^2), mean percentage error (MPE), mean bias error (MBE), root mean square error (RMSE), mean absolute relative error (MARE), and t-statistic (t-stat). These indicators can be calculated as follows (Despotovic et al. 2015).

In case of sunshine duration estimation,

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (S_{i,\mathrm{m}} - S_{i,\mathrm{c}})^2}{\sum_{i=1}^{n} (S_{i,\mathrm{m}} - S_{\mathrm{m,avg}})^2} \tag{9}$$

$$\mathrm{MPE} = \frac{1}{n} \sum_{i=1}^{n} \left(\frac{S_{i,\mathrm{c}} - S_{i,\mathrm{m}}}{S_{i,\mathrm{m}}} \times 100 \right) \tag{10}$$

$$\mathrm{MBE} = \frac{1}{n} \sum_{i=1}^{n} (S_{i,\mathrm{m}} - S_{i,\mathrm{c}}) \tag{11}$$

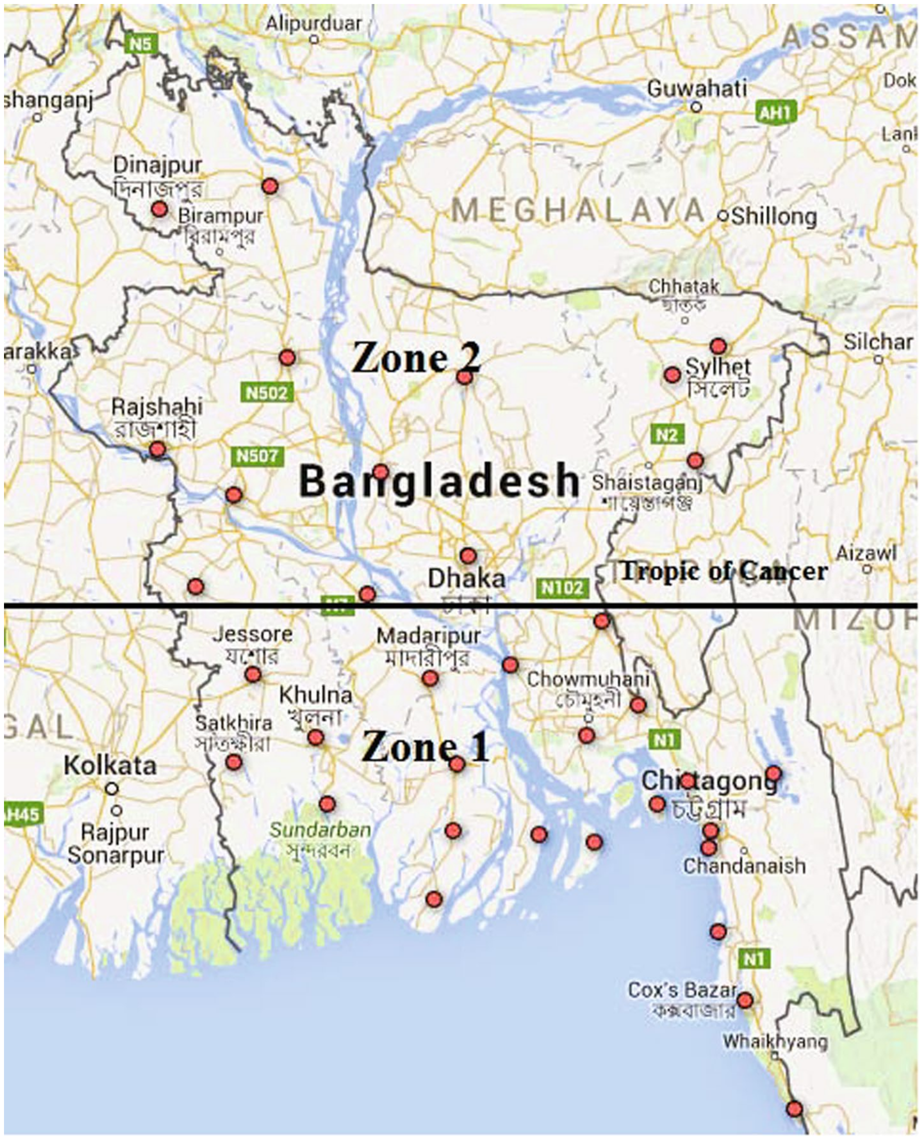

Fig. 1 Distribution of weather stations of BMD over Bangladesh

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_{i,\mathrm{m}} - S_{i,\mathrm{c}})^2} \tag{12}$$

$$\mathrm{MARE} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{S_{i,\mathrm{m}} - S_{i,\mathrm{c}}}{S_{i,\mathrm{m}}}\right| \tag{13}$$

$$t\text{-stat} = \sqrt{\frac{(n-1)\mathrm{MBE}^2}{\mathrm{RMSE}^2 - \mathrm{MBE}^2}} \tag{14}$$

where $S_{i,\mathrm{m}}$ and $S_{i,\mathrm{c}}$ are the ith measured and calculated values, respectively (h), $S_{\mathrm{m,avg}}$ is the average of the measured values (h), and n is the number of observations.

In case of solar radiation estimation,

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(H_{i,\mathrm{m}} - H_{i,\mathrm{c}})^2}{\sum_{i=1}^{n}(H_{i,\mathrm{m}} - H_{\mathrm{m,avg}})^2} \tag{15}$$

$$\mathrm{MPE} = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{H_{i,\mathrm{c}} - H_{i,\mathrm{m}}}{H_{i,\mathrm{m}}} \times 100\right) \tag{16}$$

$$\mathrm{MBE} = \frac{1}{n}\sum_{i=1}^{n}(H_{i,\mathrm{m}} - H_{i,\mathrm{c}}) \tag{17}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(H_{i,\mathrm{m}} - H_{i,\mathrm{c}})^2} \tag{18}$$

$$\mathrm{MARE} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{H_{i,\mathrm{m}} - H_{i,\mathrm{c}}}{H_{i,\mathrm{m}}}\right| \tag{19}$$

$$t\text{-stat} = \sqrt{\frac{(n-1)\mathrm{MBE}^2}{\mathrm{RMSE}^2 - \mathrm{MBE}^2}} \tag{20}$$

where $H_{i,\mathrm{m}}$ and $H_{i,\mathrm{c}}$ are the ith measured and calculated values, respectively (kWh/m^2), $H_{\mathrm{m,avg}}$ is the average of the calculated and measured values (kWh/m^2, and n is the number of observations.

For better data modeling, MPE, MBE, MARE, t-stat, and RMSE should be closer to zero, but R^2 should approach 1.0 as closely as possible.

Results and discussion

The relationship between C and $(1 - S/S_0)$ was found by plotting monthly mean values of $(1 - S/S_0)$ with corresponding monthly mean values of C for 20 stations among which 10 are below the tropic of cancer and 10 are above. At first, correlations were found separately for every stations. Then, all the values taken from Zone 1 (below 23.5°N) and from Zone 2 (above 23.5°N) were plotted to find the correlations of these two zones. Finally, all the values from all 20 stations were plotted to get an overall correlation for whole Bangladesh.

Figures 2, 3, 4, 5, and 6 show the plots achieved and their associated models with coefficient of determination (R^2) for different regions and whole Bangladesh.

From Figs. 2 and 3, it is evident that most of the points lie above the straight line $(1 - S/S_0) = C$ for cloud fraction 0 to 0.2, approximately close to the line for cloud fraction 0.3 to 0.5, and below the line for cloud fraction above 0.5. If Eq. (3) is valid, then all points should line clustered along the $(1 - S/S_0) = C$ straight line. However, as it is shown in Figs. 2, 3, 4, 5, and 6, the relationship is not linear and does not coincide with $(1 - S/S_0) = C$ line. Rather, it follows a quadratic relationship like:

$$\left(1 - \frac{S}{S_0}\right) = aC^2 + bC + c \tag{21}$$

This is because of having a systematic error in ground-based cloud cover estimation. We can see that ground-based observers have overestimated overcast conditions ($C = 0.4$–0.7) and underestimated clear days ($C = 0$–0.4). The main reason why ground-based observers overestimate overcast cloud cover seems to be that clouds with vertical extents appear to fill a greater fraction of the sky when located near the horizon than when they are overhead (Rangarajan et al. 1984). On the other hand, cloud amounts ranging from 0 to 0.4 are underestimated as in winter days (when most of the clear days are observed with low cloud amount) there are mist or fog on the ground level although the sky is clear without any cloud. The Campbell–Stokes sunshine recorder will not burn the card in this condition, but the cloud cover observer will mark it as zero cloud condition. This phenomena is usual in the northwestern part of Bangladesh.

Table 4 shows that the quadratic model gives approximately maximum goodness of fit. Then increasing the order of the equation further does not increase the R^2 value significantly. Therefore, in this study the higher-degree models were not considered for sunshine duration estimation.

Tables 5 and 6 show the values of regression coefficients of quadratic model for sunshine duration estimation from cloud fraction and their corresponding statistical evaluation. For all the models either regional, zonal, or countrywide, the value of RMSE did not exceed 0.8 and most of the time remained below 0.5. The MARE values also showed promising results with less than 0.1 for most of the cases. The MPE also remained less than 10 %, and MBE also remained less than 0.5.

Now, comparing all the results we can see that regional models give best fit with the value of R^2 ranging from 0.9 to 0.99, whereas models for Zone 1 and Zone 2 also performed well with little less accuracy and fit. The overall model for whole Bangladesh also performed quite well and sometimes better than the zonal models.

As using different models for different regions is quite difficult and the accuracy is not that much deviated, we suggest the following equations for estimation of sunshine duration from cloud amount in Bangladesh:

For Zone 1 (≤23.5°N):

$$\left(1 - \frac{S}{S_0}\right) = 0.4284C^2 + 0.2462C + 0.2144 \tag{22}$$

For Zone 2 (≥23.5°N):

$$\left(1 - \frac{S}{S_0}\right) = 0.5102C^2 + 0.0911C + 0.2703 \tag{23}$$

For whole Bangladesh:

$$\left(1 - \frac{S}{S_0}\right) = 0.4548C^2 + 0.1851C + 0.2385 \tag{24}$$

Now using calculated monthly mean values of S from the corresponding mean of C, we can compute monthly

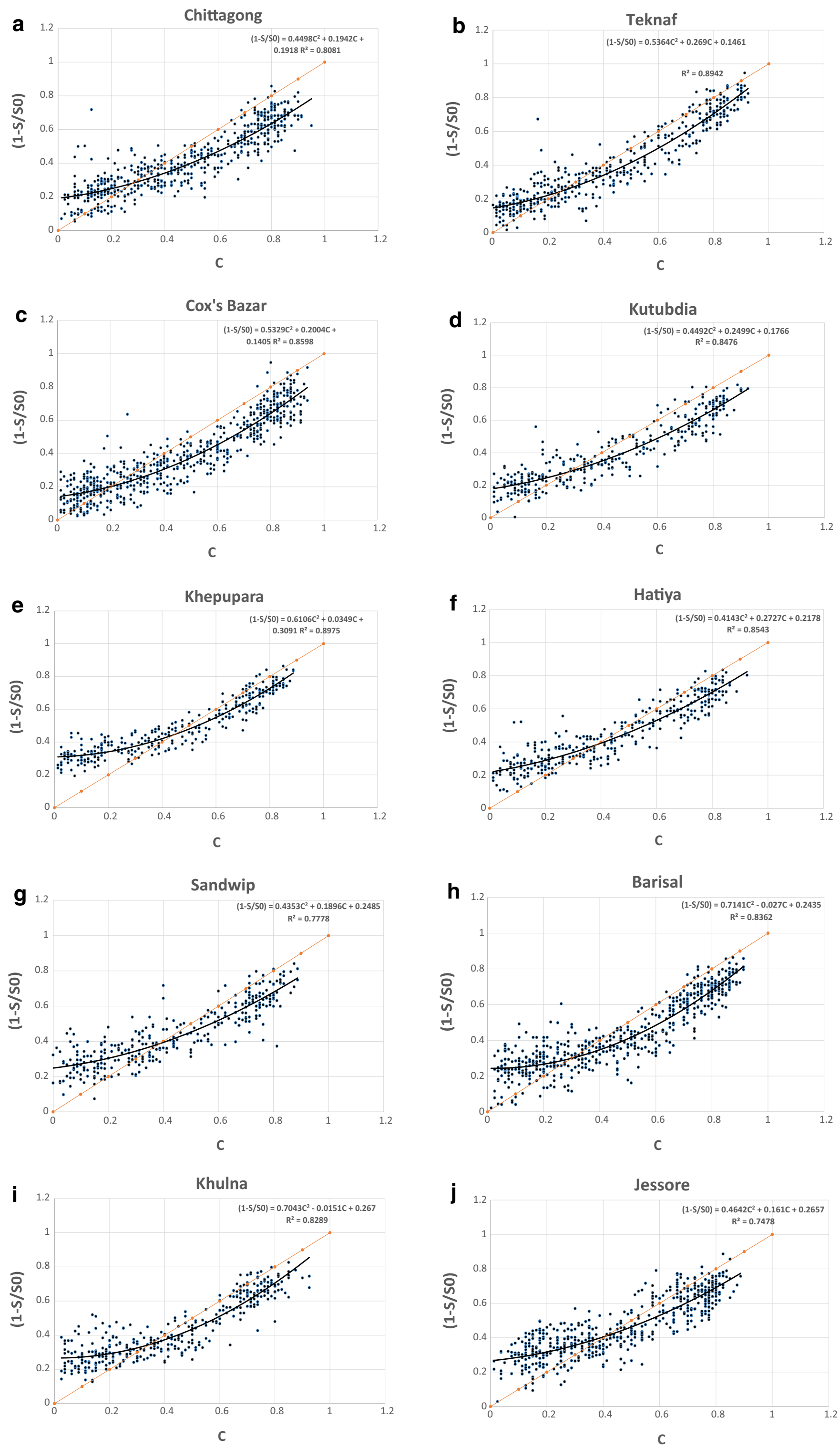

Fig. 2 Correlation between C and $(1 - S/S_0)$ for different regions of Zone 1

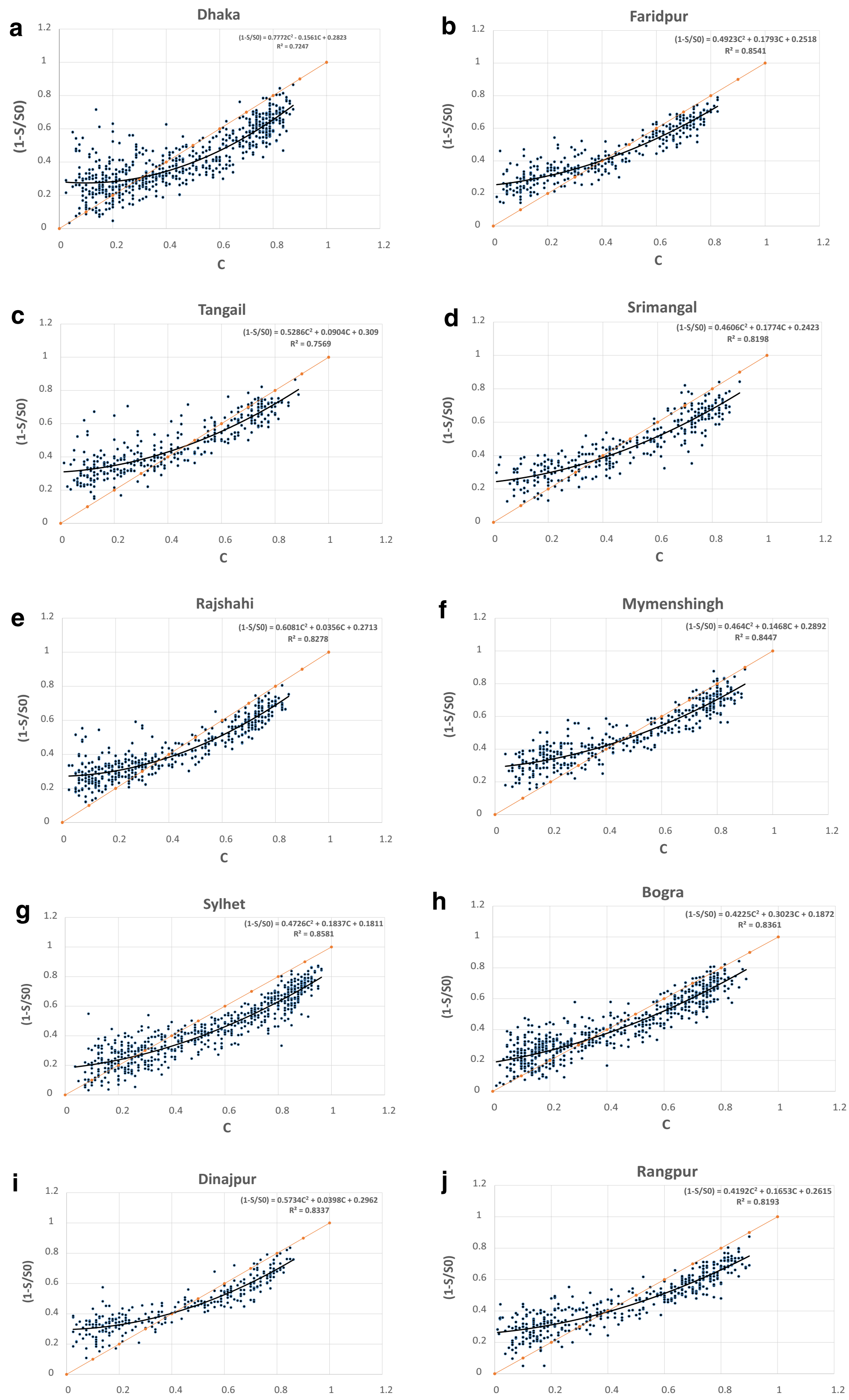

Fig. 3 Correlation between C and $(1 - S/S_0)$ for different regions of Zone 2

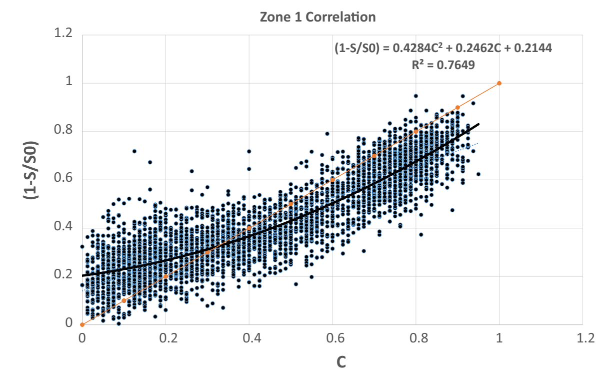

Fig. 4 Correlation between C and $(1 - S/S_0)$ for Zone 1

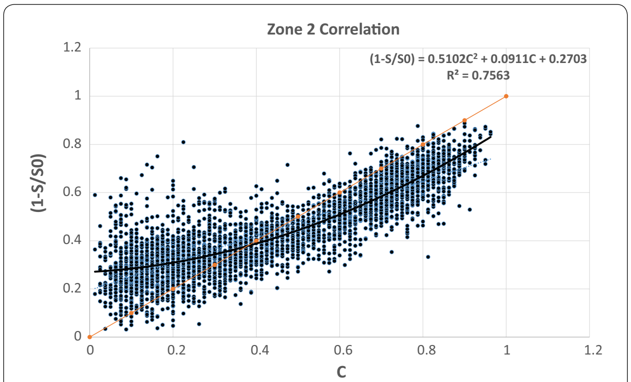

Fig. 5 Correlation between C and $(1 - S/S_0)$ for Zone 2

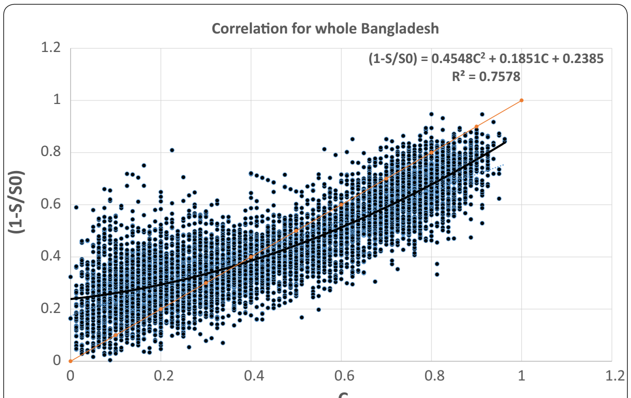

Fig. 6 Correlation between C and $(1 - S/S_0)$ for whole Bangladesh

mean values of global solar radiation H using standard techniques developed by other researchers (Sen 2007; Al-Mostafa et al. 2014).

Table 7 shows different models to estimate solar radiation directly from cloud cover data. After the statistical error test, it is seen that the higher-degree models perform better with lowest RMSE values. The fifth-degree model performs best, but to avoid complexity one can easily use quadratic or third-degree model to estimate solar radiation. Considering both, the simplicity of the model and accuracy, we can recommend the third-degree or cubic model for use:

$$H/H_0 = 1.9104C^3 - 3.1785C^2 + 1.3352C + 0.3669 \quad (25)$$

Finally, Table 3 shows that we have measured global solar radiation field data only for five stations of BMD, and those were only for 1 year for all the four stations except Dhaka. Therefore, we have chosen Dhaka station's data to compare all the methods of estimation. Figure 7 shows the comparison of different estimated and measured global solar radiation (H) of Dhaka, Bangladesh, and it is evident that all the models performed quite well and give approximately close estimation of solar radiation for Dhaka.

Figure 8 shows the comparative errors in global solar radiation estimation of different methods. We can see from the figure that estimating solar radiation from sunshine duration gives the best estimation with quite low RMSE value of 0.13 (kWh/m^2). However, if there is no sunshine duration data available for a site, then it is better to estimate solar radiation from direct cloud cover estimation models. Estimating sunshine duration first from cloud data to estimate solar radiation introduces more error as it has to go through the modeling stage twice. In case of requirement of sunshine duration data, the estimation from cloud cover data is quite helpful and gives quite close estimation.

Conclusions

As a developing country with very less investment in technology to measure solar radiation directly, Bangladesh needs models to estimate solar radiation from other climatological data like cloud cover. Therefore, both the models to estimate sunshine hours from cloud cover of various regions of Bangladesh are established along with models to estimate solar radiation directly from cloud cover data. As sunshine hour has a latitudinal dependence, two general models for Zone 1 $\leq$23.5° and Zone 2 $\geq$23.5° are developed to estimate sunshine hours with better accuracy. Finally, a quadratic relationship for whole Bangladesh is proposed. In case of models to estimate solar radiation directly from cloud cover data, few linear and higher-order models are proposed. All the developed models are checked statistically. The value of RMSE did not exceed 0.8, and most of the time remained below 0.5. The MARE values also showed promising results with less than 0.1 for most of the cases. The MPE also remained less than 10 %, and MBE also remained

Table 4 Different models to estimate sunshine duration from cloud fraction of Bangladesh and their equations with coefficient of determination

Model type	Model equations	Goodness of fit (R^2)
Linear	$(1 - S/S_0) = 0.6034C + 0.1739$	0.7402
Qudratic	$(1 - S/S_0) = 0.4548C^2 + 0.1851C + 0.2385$	0.7578
Third degree	$(1 - S/S_0) = -0.0855C^3 + 0.5721C^2 + 0.1409C + 0.2424$	0.7578
Fourth degree	$(1 - S/S_0) = -2.6566C^4 + 4.8588C^3 - 2.4378C^2 + 0.7996C + 0.2039$	0.7597
Fifth degree	$(1 - S/S_0) = 0.273C^5 - 3.2931C^4 + 5.3912C^3 - 2.6292C^2 + 0.8272C + 0.2028$	0.7597

Table 5 Correlation coefficients of quadratic model for sunshine duration estimation from cloud fraction and statistical error tests of different stations of Zone 1

Stations	Model	*a*	*b*	*c*	R^2	MPE	MBE	MARE	RMSE	*t*-stat
Teknaf	Regional	0.5364	0.269	0.1461	0.9848	1.7305	−0.0541	0.0498	0.2808	0.6511
	Zone 1	0.4284	0.2462	0.2144	0.9309	−0.8473	0.2748	0.0902	0.5985	1.714
	Countrywide	0.4548	0.1851	0.2385	0.9038	−0.8258	0.3196	0.1057	0.7064	1.6829
Cox's Bazar	Regional	0.5329	0.2004	0.1405	0.9699	1.7093	−0.066	0.0506	0.3511	0.6356
	Zone 1	0.4284	0.2462	0.2144	0.8405	−9.3925	0.707	0.1024	0.8083	5.9863
	Countrywide	0.4548	0.1851	0.2385	0.8157	−9.4079	0.7441	0.1083	0.8688	5.5043
Kutubdia	Regional	0.4492	0.2499	0.1766	0.9644	1.4224	−0.0627	0.0413	0.3178	0.6684
	Zone 1	0.4284	0.2462	0.2144	0.9325	−3.9831	0.3033	0.0557	0.4376	3.1897
	Countrywide	0.4548	0.1851	0.2385	0.9141	−4.1987	0.3461	0.0656	0.4939	3.2588
Khepupara	Regional	0.6106	0.0349	0.3091	0.9505	−0.6233	0.0511	0.0467	0.3421	0.5018
	Zone 1	0.4284	0.2462	0.2144	0.8192	9.3429	−0.5197	0.1019	0.654	4.341
	Countrywide	0.4548	0.1851	0.2385	0.8447	9.2113	−0.4843	0.101	0.6061	4.4085
Hatiya	Regional	0.4143	0.2727	0.2178	0.9498	2.7677	−0.1187	0.0486	0.3709	1.1207
	Zone 1	0.4284	0.2462	0.2144	0.9255	5.342	−0.2591	0.0653	0.4519	2.3214
	Countrywide	0.4548	0.1851	0.2385	0.9168	5.1502	−0.219	0.0698	0.4777	1.7109
Chittagong	Regional	0.4498	0.1942	0.1918	0.9434	2.2874	−0.0931	0.0506	0.3805	0.8374
	Zone 1	0.4284	0.2462	0.2144	0.8871	−5.8735	0.4022	0.0716	0.5374	3.7416
	Countrywide	0.4548	0.1851	0.2385	0.8778	−5.9425	0.4325	0.0761	0.5591	4.0474
Sandwip	Regional	0.4353	0.1896	0.2485	0.899	4.823	−0.2205	0.0625	0.4491	1.8692
	Zone 1	0.4284	0.2462	0.2144	0.8844	6.5565	−0.3583	0.0705	0.4803	3.7146
	Countrywide	0.4548	0.1851	0.2385	0.8834	6.1214	−0.3089	0.0693	0.4824	2.7645
Rangamati	Regional	0.7043	−0.0151	0.267	0.9123	3.9047	−0.1673	0.0619	0.4377	1.3727
	Zone 1	0.4284	0.2462	0.2144	0.8972	4.5865	−0.1984	0.0656	0.4738	1.5293
	Countrywide	0.4548	0.1851	0.2385	0.883	4.5021	−0.1718	0.0716	0.5056	1.1982
Barisal	Regional	0.7141	−0.027	0.2435	0.9698	2.3692	−0.0989	0.044	0.2998	1.1589
	Zone 1	0.4284	0.2462	0.2144	0.9454	−0.8815	0.1138	0.0506	0.4031	0.9764
	Countrywide	0.4548	0.1851	0.2385	0.9391	−0.8889	0.1434	0.0543	0.4258	1.1867
Maijdee Court	Regional	0.7043	−0.0151	0.2670	0.8936	6.4040	−0.3615	0.0783	0.4995	3.4782
	Zone 1	0.4284	0.2462	0.2144	0.8415	8.4215	−0.4696	0.0925	0.6098	4.0045
	Countrywide	0.4548	0.1851	0.2385	0.8626	8.1031	−0.4228	0.0871	0.5678	3.6997
Jessore	Regional	0.4642	0.1610	0.2657	0.9292	2.6934	−0.1368	0.0480	0.3677	1.3294
	Zone 1	0.4284	0.2462	0.2144	0.8339	6.6521	−0.4023	0.0730	0.5633	3.3839
	Countrywide	0.4548	0.1851	0.2385	0.8684	6.3433	−0.3619	0.0709	0.5014	3.4590
Khulna	Regional	0.7043	−0.0151	0.2670	0.9109	5.9973	−0.2692	0.0712	0.4829	2.2271
	Zone 1	0.4284	0.2462	0.2144	0.8764	7.1841	−0.3415	0.0859	0.5687	2.4906
	Countrywide	0.4548	0.1851	0.2385	0.8722	6.7666	−0.2903	0.0857	0.5783	1.9253

Table 6 Correlation coefficients of quadratic model for sunshine duration estimation from cloud fraction and statistical error tests of different stations of Zone 2

Stations	Model	*a*	*b*	*c*	R^2	MPE	MBE	MARE	RMSE	*t*-stat
Faridpur	Regional	0.4923	0.1793	0.2518	0.9355	−1.5308	0.0807	0.0412	0.3255	0.8489
	Zone 2	0.5102	0.0911	0.2703	0.9514	2.1836	−0.1116	0.0375	0.2826	1.4264
	Countrywide	0.4548	0.1851	0.2385	0.9359	2.6308	−0.1623	0.0384	0.3247	1.9139
Dhaka	Regional	0.7772	−0.1561	0.2823	0.9585	0.1666	0.0000	0.0368	0.2820	0.0000
	Zone 2	0.5102	0.0911	0.2703	0.8751	−5.0073	0.3470	0.0612	0.4894	3.3349
	Countrywide	0.4548	0.1851	0.2385	0.8672	−4.8924	0.3180	0.0637	0.5046	2.6918
Ishurdi	Regional	0.6081	0.0356	0.2713	0.9126	0.3645	−0.0338	0.0401	0.3831	0.2940
	Zone 2	0.5102	0.0911	0.2703	0.9190	1.0880	−0.0549	0.0433	0.3688	0.4994
	Countrywide	0.4548	0.1851	0.2385	0.8837	1.5396	−0.1044	0.0476	0.4420	0.8062
Tangail	Regional	0.5286	0.0904	0.3090	0.9152	1.4147	−0.0402	0.0538	0.3871	0.3470
	Zone 2	0.5102	0.0911	0.2703	0.7352	10.5005	−0.5564	0.1053	0.6845	4.6278
	Countrywide	0.4548	0.1851	0.2385	0.7047	10.9350	−0.6054	0.1093	0.7227	5.0868
Srimangal	Regional	0.6081	0.0356	0.2713	0.7843	8.3236	−0.4115	0.0931	0.6273	2.8828
	Zone 2	0.5102	0.0911	0.2703	0.7496	8.6157	−0.4109	0.1012	0.6759	2.5393
	Countrywide	0.4548	0.1851	0.2385	0.7721	9.0217	−0.4599	0.0965	0.6447	3.3764
Rajshahi	Regional	0.6081	0.0356	0.2713	0.9384	1.0918	−0.0559	0.0408	0.3268	0.5761
	Zone 2	0.5102	0.0911	0.2703	0.9293	1.5105	−0.0615	0.0435	0.3501	0.5920
	Countrywide	0.4548	0.1851	0.2385	0.9233	2.1406	−0.1253	0.0420	0.3646	1.2136
Mymenshingh	Regional	0.4640	0.1468	0.2892	0.8973	−1.5783	0.0525	0.0577	0.3751	0.4693
	Zone 2	0.5102	0.0911	0.2703	0.8450	5.1715	−0.3305	0.0530	0.4608	3.4153
	Countrywide	0.4548	0.1851	0.2385	0.7744	5.4347	−0.3680	0.0577	0.5559	2.9286
Sylhet	Regional	0.4726	0.1837	0.1811	0.9696	1.4943	−0.0670	0.0428	0.2979	0.7662
	Zone 2	0.5102	0.0911	0.2703	0.8629	−8.6237	0.5557	0.0929	0.6327	6.0960
	Countrywide	0.4548	0.1851	0.2385	0.8685	−9.0145	0.5502	0.0918	0.6195	6.4128
Bogra	Regional	0.4225	0.3023	0.1872	0.9447	0.7061	−0.0651	0.0400	0.3342	0.6587
	Zone 2	0.5102	0.0911	0.2703	0.9368	−0.5272	0.0957	0.0428	0.3573	0.9225
	Countrywide	0.4548	0.1851	0.2385	0.9569	−0.0382	0.0379	0.0384	0.2950	0.4306
Dinajpur	Regional	0.5734	0.0398	0.2962	0.8849	3.6956	−0.2112	0.0578	0.4080	2.0072
	Zone 2	0.5102	0.0911	0.2703	0.7796	7.4499	−0.4435	0.0778	0.5646	4.2089
	Countrywide	0.4548	0.1851	0.2385	0.7421	8.3670	−0.5273	0.0836	0.6109	5.6691
Syedpur	Regional	0.6081	0.0356	0.2713	0.9194	2.5952	−0.1678	0.0448	0.3230	2.0160
	Zone 2	0.5102	0.0911	0.2703	0.9168	3.0251	−0.1768	0.0462	0.3282	2.1209
	Countrywide	0.4548	0.1851	0.2385	0.8961	3.5404	−0.2300	0.0509	0.3666	2.6720
Rangpur	Regional	0.4192	0.1653	0.2615	0.7947	6.5107	−0.3662	0.0771	0.5369	3.0928
	Zone 2	0.5102	0.0911	0.2703	0.7938	6.6344	−0.3794	0.0764	0.5380	3.2992
	Countrywide	0.4548	0.1851	0.2385	0.7547	7.2168	−0.4364	0.0772	0.5868	3.6901

Table 7 Regression models to estimate solar radiation directly from cloud cover fraction

#	Model type	Equations	R^2	MBE	MPE	MARE	RMSE	*t*-stat
1	Linear	$H/H_0 = -0.2302C + 0.5713$	0.9936	0.0213	0.6566	0.0716	0.3315	0.2139
2	Quadratic	$H/H_0 = -0.4585C^2 + 0.2087C + 0.4942$	0.9953	0.0157	0.4905	0.0585	0.2834	0.1850
3	Third degree	$H/H_0 = 1.9104C^3 - 3.1785C^2 + 1.3352C + 0.3669$	0.9954	0.0135	0.4482	0.0481	0.2831	0.1593
4	Fourth degree	$H/H_0 = -11.449C^4 + 23.22C^3 - 16.729C^2 + 4.7227C + 0.0963$	0.9957	0.0008	0.8008	0.0543	0.2721	0.0098
5	Fifth degree	$H/H_0 = 120.19C^5 - 299.15C^4 + 281.59C^3 - 124.07C^2 + 25.073C - 1.3032$	0.9974	0.0151	0.1131	0.0344	0.2107	0.2395
6	Logarithmic	$H/H_0 = -0.083\ln(C) + 0.386$	0.9905	0.0164	0.8877	0.0909	0.4052	0.1347
7	Exponential	$H/H0 = 0.5819exp^{(-0.509C)}$	0.9931	0.0362	0.3475	0.0728	0.3445	0.3505
8	Power	$H/H0 = 0.3862C^{(-0.184)}$	0.9899	0.0376	0.4436	0.0916	0.4184	0.2994

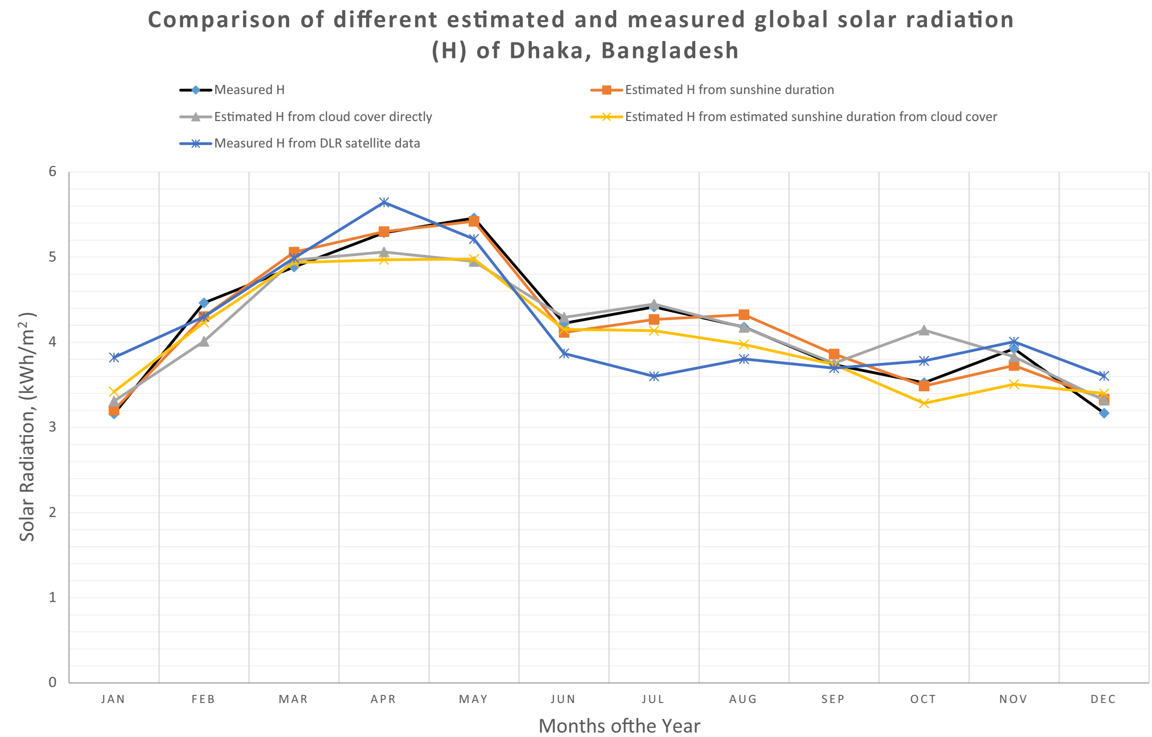

Fig. 7 Comparison of different estimated and measured global solar radiation (*H*) of Dhaka, Bangladesh

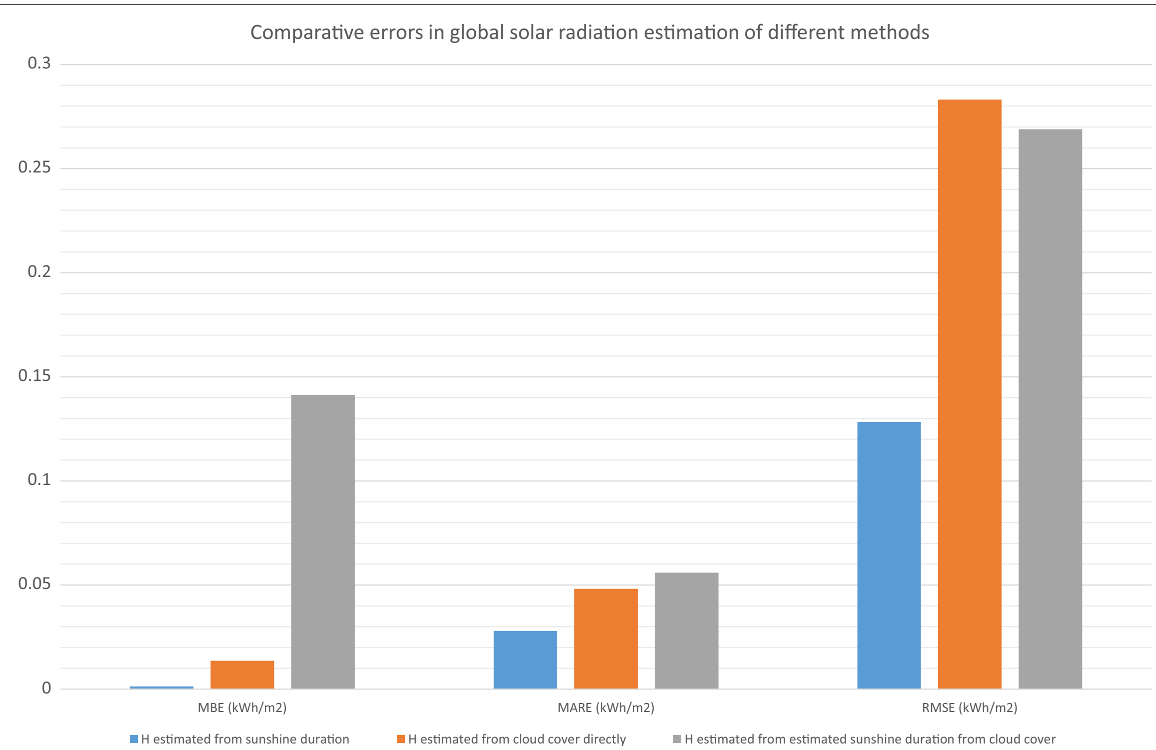

Fig. 8 Comparative errors in global solar radiation estimation of different methods

less than 0.5. The regional models give best fit with the value of R^2 ranging from 0.9 to 0.99, Whereas sunshine duration measurement models for Zone 1 and Zone 2 also performed well with little less accuracy and fit.

As using different models for different regions is quite difficult and the accuracy is not that much deviated, we suggest the model developed for whole Bangladesh in Eq. (24) to be used for estimation of sunshine duration from cloud amount in Bangladesh. On the other hand, Eq. (25) can be used to estimate solar radiation directly from cloud fraction in Bangladesh. It is also seen from the study that for a small country like Bangladesh separating data according to latitude has no significant effect.

Finally, it is always better to estimate solar radiation from sunshine duration as it gives the best estimation with quite less error. However, if there is no sunshine duration data available for a site, then solar radiation can be estimated directly from cloud cover data. Estimating sunshine duration first from cloud data to estimate solar radiation introduces more error as it has to go through the modeling stage twice. In case of requirement of sunshine duration data, the estimation from cloud cover is quite helpful.

List of symbols

H	global solar radiation on the horizontal surface (kWh/m^2)
H_0	extraterrestrial solar radiation (kWh/m^2)
C	cloud fraction
S	sunshine duration (h)
S_0	maximum possible hours of sunshine of a day (h)
D	day number of the year counting from first January
ϕ	latitude (°)
ω_s	sunset hour angle (°)
δ	solar declination (°)
R^2	coefficient of determination
MPE	mean percentage error
MBE	mean bias error
RMSE	root mean square error
MARE	mean absolute relative error
t-stat	t-statistic

Subscripts

i	ith value
m	measured
c	calculated
avg	average

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Competing interests
The author declare that he has no competing interests.

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