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Evaluating the Solar Radiation System under the Climatic Condition of Dhaka, Bangladesh and Computing the Angstrom Coefficients

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ABSTRACT

In this research work some mathematical models have been simulated to estimate the regression coefficients, which are also known as Angstrom coefficients, with monthly and daily average solar radiation on horizontal surface using bright sunshine hours. This study of solar energy, information on solar radiation and its components at a given location is very essential for scientists, engineers, architects, agriculturists and hydrologists for various applications such as measuring aerosol optical thickness, solar heating, cooking, drying and interior illumination of buildings. But, for developing countries like Bangladesh, we have limitation of sophisticated measuring instruments. So, we have used some latitude based empirical models to calculate an important solar radiation geometry parameter- Angstrom Coefficients for Bangladesh without any help of costly instruments.

Key words: Global radiation, Regression coefficient, Hour angle, Day length, System dynamics methodology.

INTRODUCTION

Strictly speaking, all forms of energy on the earth are derived from the sun. However, the more conventional forms of energy, the fossil fuels received their solar energy input eons ago and process the energy in a greatly concentrated form. Solar radiation on a ground level horizontal surface is the first input for the performance calculations of solar energy systems. Technology for measurement of solar radiation is costly and has instrumental hazard [1] for many developing countries like Bangladesh. In such cases we need the estimation models which use other climatologically measurements and/or geographical parameters based on readily available meteorological data. For this, several empirical models have been developed to calculate global solar radiation using various parameters. Angstrom [2] developed the earliest model used for estimating global radiation, in which the sunshine duration data and clear sky radiation data were used. Because there may be problems in calculating clear sky radiation accurately, by replacing clear sky radiation with extraterrestrial radiation, this model was modified to a more convenient form by Prescott in 1940 [10]. In this paper a mathematical model has chosen to simulate the availability of solar radiation in Bangladesh using system dynamics methodology. For this, some solar radiation geometry parameters will be frequently used for calculation purpose [7].

MATERIALS AND METHODS

The solar radiation geometry parameters, we have to consider are following –

Solar Constant (I_{sc}): The rate at which energy is received from the sun on a unit area perpendicular to the rays of the sun at a mean distance of the earth from the sun. The modern value of I_{sc} is 1367 w/m^2.

Extraterrestrial Radiation (I'_{sc}): The radiation outside the atmosphere is called extraterrestrial radiation. The quantity of extraterrestrial radiation for a particular day is $I'_{sc} = I_{sc}\left(1+0.033\cos\frac{360n}{365}\right)$; where, n is the day of the year.

Beam Radiation (I_b): The part of the radiation, falls on the earth surface through the atmosphere, directly from the sun. It is also called Direct Radiation.

Diffuse Radiation (I_d): The part of the radiation falls on the earth surface due to scattering, absorption reflection and refraction by the air molecule.

Albedo (I_a): The part of the radiation reflected by the earth surface to the atmosphere.

Global Radiation (I_g): The Algebraic sum of the beam, diffuse and albedo radiation is called Global Radiation.

i.e. $I_g = I_b + I_d + I_a$

Hour Angle (ω): The hour angle is an angular measurement of time and equivalent to 15^o per hour. It is measured from noon based on Local Apparent Time (LAT) / Solar Time, being *+ve* in the morning and *–ve* in the afternoon.

Angle of Incident (θ): The angle made by incident ray and the normal is called angle of incident.

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Tilt / Slope Angle (β): The angle made by plane surface with the horizontal is called tilt angle. It is negative for surface sloping towards the north.

Declination Angle (δ): The angle made by the line joining the centers of the sun and the earth with its projection on the equatorial plane. The relation is

$$\delta = 23.45\sin\left[\frac{360(284+n)}{365}\right]$$; where n is the number of day.

Surface Azimuthal Angle (γ): The angle made in the plane between the line due south and projection of the normal to the surface on the horizontal plane. It is vary +180° to -180°. We accept east of south for +ve west of south for –ve.

Solar Time / Local Apparent Time (LAT): LAT is defined by the following equation-

LAT = Standard/clock time ± [Standard time longitude – Longitude of location (φ)] × $\frac{1hr}{15^o}$ + Equation of time correction (E); where

$$E = 9.87\sin 2B - 7.53\cos B - 1.5\sin B;$$

where $B = \frac{360(n-81)}{364}$.

For eastern hemisphere *–ve* and for western hemisphere *+ve*.

Angle of Incidence (θ): The angle of incidence for solar radiation can be calculated from the following equation-

$$\cos\theta = \sin\phi(\sin\delta\cos\beta + \cos\gamma\cos\delta\cos\omega\sin\beta) + \cos\phi(\cos\delta\cos\omega\cos\beta - \sin\delta\cos\gamma\sin\beta) + \cos\delta\sin\gamma\sin\omega\sin\beta$$

where ϕ is latitude.

Day Length (S_{max}): The time duration between sun rise and sun shine is called day length.

The hour angle (ω_s) corresponding to sunrise or sunset on a horizontal surface [1] is-

$$\omega_s = \cos^{-1}(-\tan\phi\tan\delta) \quad (1)$$

Since 15° of the hour angle is equivalent to 1 hour, the corresponding day length-

$$S_{max} = \frac{2}{15}\omega_s \quad (2)$$

Almost all the models developed for the estimation of the solar radiation have a physical basis and mostly used the form

$$G = G_0\phi_c f(\alpha) \quad (3)$$

Where G is the incident global irradiation, G_0 is the theoretical irradiation in the cloud free atmosphere, ϕ_c is a cloud transmittance for global irradiance and $f(\alpha)$ is a function of ground albedo and atmospheric back-scattering [4]. ϕ_c can be expressed in terms of cloud amount C or with an assumption $C = 1 - \frac{s_c}{S_c}$, in terms of the fractional number of sunshine duration s_c/S_c, where S_c and s_c are the maximum possible and the measured number of sunshine duration within an infinitesimal time interval respectively. If the function ϕ_c is expressed in terms of s_c then these models are called the sunshine – based models.

Using Equation (3) and assuming a linear relation between ϕ_c and s_c/S_c, we get-

$$G = G_0\left[A + B\left(\frac{s_c}{S_c}\right)\right]f(\alpha) \quad (4)$$

Now, neglecting the effect of multiple reflections between the ground and the atmosphere the basis of the Angstrom equation (2) will be-

$$G = G_0\left[A + B\left({s_c}/{S_c}\right)\right] \quad (5)$$

For the monthly average daily solar radiation the Angstrom equation is [by analogy with equation (5)]

$$H/H_c = a' + b'(s/S) \quad (6)$$

Where H and H_c are the monthly average value of the global solar radiation and theoretical radiation in the cloud free atmosphere, s and S are monthly average bright sunshine hour and day length. Equation (6) was modified by Prescott in 1940 [10] and Page in 1964 [9]. So, the equation (6) will be

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

The coefficients a and b depend on the seasonal and regional parameters and are known as the Angstrom coefficients. The 'a' coefficient can be interpreted as the fraction of the monthly average solar radiation (H/H_0) entering the atmosphere when there is a complete cloud cover. The second coefficient 'b' defines the rate of change of H/H_0 with respect to s/S and it is an index of the latitudinal variation of equation (7) [11].

Equation (7) is one of the simplest models used to estimate monthly average daily global radiation on horizontal surface in the modified form of the Angstrom-type equation. But to estimate the coefficients, some latitude (φ) proposed regression models can be considered are given bellow.

Model 1:

Rietveld examined several published values of the a and b from following equations respectively [12]-

$$a = 0.10 + 0.24\left(\frac{s}{S}\right)$$

$$b = 0.38 + 0.08\left(\frac{s}{S}\right) \quad (8)$$

Model 2:
Gariepy has reported that the empirical coefficient *a* and *b* are dependent on mean air temperature (*T*) and the amount of precipitation (*P*) [5]-

$$a = 0.3791 - 0.0041(T) - 0.0176(P)$$
$$b = 0.4810 + 0.0043(T) + 0.0097(P) \quad (9)$$

Model 3:
Kilic and Ozturk [8] have determined that the coefficients *a* and *b* are a function of the solar declination (δ) in addition to both φ and *Z* is, as given by the following equations -

$$a = 0.103 + 0.017Z + 0.198\cos(\varphi - \delta)$$
$$b = 0.533 - 0.165\cos(\varphi - \delta) \quad (10)$$

Model 4:
Dogniaux and Lemoine have also proposed following equation, where the regression coefficients *a* and *b* seem to be as a function of φ in average and on the monthly base in these equations, respectively-

$$a = 0.37022 - 0.00313(\varphi)$$
$$b = 0.32029 + 0.00506(\varphi) \quad (11)$$

Model 5:
Zabara proposed monthly *a* and *b* values of the modified Angstrom model as a third order function of maximum possible sunshine duration (*s*) and (*S*) [14]

$$a = 0.395 - 1.274\left(\frac{s}{S}\right) + 2.680\left(\frac{s}{S}\right)^2 - 1.674\left(\frac{s}{S}\right)^3$$
$$b = 0.395 + 1.384\left(\frac{s}{S}\right) - 3.249\left(\frac{s}{S}\right)^2 + 2.055\left(\frac{s}{S}\right)^3 \quad (12)$$

Model 6:
Gopinathan has suggested that the coefficients *a* and *b* are a function of (*s*/*S*) and the altitude of the site (*Z*) as given by the equations given as follow [6]-

$$a = 0.265 + 0.07Z - 0.135\left(\frac{s}{S}\right)$$
$$b = 0.401 - 0.108Z + 0.325\left(\frac{s}{S}\right) \quad (13)$$

Model 7:
While Soler has given a modified Angstrom type equation for each month, then the regression coefficients of *a* and *b* was also found for 100 station [13]-

$$a = 0.179 + 0.099\left(\frac{s}{S}\right)$$
$$b = 0.1640 + 0.1786\left(\frac{s}{S}\right) - 1.0935\left(\frac{s}{S}\right)^2 \quad (14)$$

Model 8:
Collres-Pereira and Rabl [3] developed an analytical expression for the ratio of hourly to daily global radiation, where the coefficients *a* and *b* are defined by-

$$a = 0.409 + 0.5016\sin(\omega_s - 60)$$
$$b = 0.6609 - 0.4767\sin(\omega_s - 60) \quad (15)$$

Model 9:
Neuwirth related *a* and *b* to altitude, *h* above sea level by quadratic regression and he obtained the relations-

$$a = A_0 + A_1 h + A_2 h^2$$
$$b = B_0 + B_1 h + B_2 h^2 \quad (16)$$

He gave the values of A_0, A_1, A_2 and B_0, B_1, B_2 for each season and these values are presented in Table 1.

RESULTS AND DISCUSSION

Above models can be used to calculate the regression coefficients without help of so much sophisticated and costly instruments. Because, we can evaluate the values just calculating the sunset hour angle (ω_s), which we can get from equation (1). But, still we need long term data and other measurement of parameters for the particular location to use equation (1). For this, we have tried to figure out another method to find out the regression / Angstrom coefficients.

Basically, Angstrom coefficients are computed using observations of monthly average sunshine hours and day length. Because, values comes from these models are the most accurate. But this process requires a long term data for the particular locations which is practically difficult. So, we have to consider two ways- either use costly instruments to measure the different parameter of solar geometry or use any established mathematical models like model 8 or model 3 and 4. We find that results from Model 8 are the most acceptable considering all of our instrumental limitations. Some results obtained from model 8 are shown in Table 2. The variation of *a* and *b* over the year have shown in the graph (Fig. 1). From the fig we have seen that when *a* is increased *b* is decreased and vice-versa. It is clear that in the middle of June both Coefficients have become their optimum value which are maximum and minimum value of *a* and *b* respectively. So a reverse characteristic exists between *a* and *b*.

CONCLUSION

Solar radiation data are essential in the design and study of solar energy conversation devices. In this regard, empirical correlations are developed to estimate the monthly average daily global radiation on a horizontal surface. But, Angstrom coefficients play an important role to calculate the global radiation (eqn. 7). Our studies and analysis of different data of various parameters prove that sunshine based models are more trusted. But equation (15) is the best model to calculate the regression coefficients of a particular day considering the climatic condition as well as the socio economic scenario of Bangladesh.

Table1: (A_0-B_3) Variation with respect to seasons.

	A_0	A_1	A_2	B_0	B_2	B_3
Winter	0.1494	0.1192	-0.0117	0.5498	-0.2062	0.0492
Spring	0.1711	0.1261	-0.0108	0.5403	-0.1813	0.0395
Summer	0.2051	0.0234	0.0078	0.4972	-0.0693	0.0199
Autumn	0.1917	0.0210	0.0073	0.4921	-0.0428	0.0091

Table 2: Angstrom coefficients *a* and *b* for particular month

Month	***a***	***b***
January	0.5833	0.4953
February	0.6144	0.4657
March	0.6517	0.4302
April	0.6908	0.3930
May	0.7221	0.3634
June	0.7369	0.3493
July	0.7303	0.3556
August	0.7043	0.3803
September	0.6671	0.4156
October	0.6268	0.4539
November	0.5912	0.4875
December	0.5742	0.5039

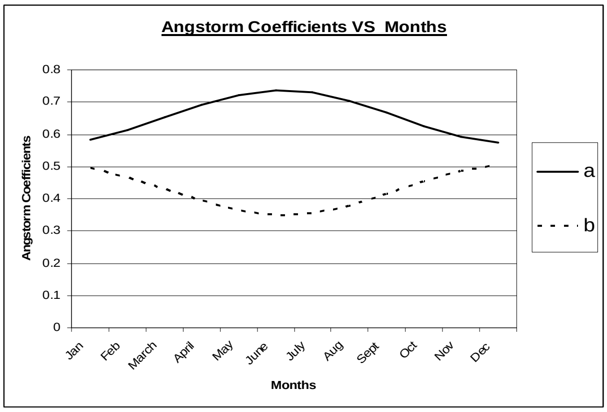

Fig. 1: Variation of the Angstrom coefficients (*a and b*) with the variation of different months of the year.

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