USE OF RAINFALL DATA TO CALCULATE INCIDENT SOLAR RADIATION IN TROPICAL COUNTRIES

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Abstract: Determining the incident solar radiation for a given location is an important aspect of any solar related application. Though solar radiation data are available at weather stations, localized nature of solar radiation due to topographic and climatic parameters demands measured or calculated solar radiation values for a given location for accurate results. Many correlations have been developed over the past few decades yielding solar radiation values from various weather parameters such as daily sunshine duration, ambient temperature difference, relative humidity, cloud cover etc.

However, most of the weather data are practically difficult and costly to record hence requiring a simplistic approach to the issue. For any geographical location the cloud cover plays a major role in controlling the incident solar radiation. In tropical countries, where the climate is highly humid, cloud cover is closely related to rainfall. Therefore, day time rainfall data can be taken as representative of overcast and clear days, paving the way to calculate the clearness index, K_T using equations developed on cloud cover data.

***Key Words**: Solar radiation, Rainfall, Cloud cover, Clearness index*

1. Introduction

Determining of average global solar radiation incident at a given location is usually carried out by long term direct measurement or using correlations developed through research using weather data. Of the two methods, long term direct measurement of solar radiation, other than that carried out at weather stations, are found to be low in accuracy due to cost of maintenance of equipment and requirement of skilled labor over an extended period of time. A relatively new development is the prediction of incident solar radiation using satellite technology, combining both the direct measurement and correlation methods, where collected data are simulated over a long period of time. However, the predicted values are found to be accurate only within a limited geographical region of 50 km radius from a given weather station (Cano) (11), hence rendering the values obtained from satellite technology useful only in gross calculations.

Correlations developed to predict solar radiation using weather parameters on the other hand are much more practical provided the relevant weather data are easily obtainable. Of the correlations developed, Angstrom (3) type is the most widely used with daily sunshine duration as the input. For tropical countries, the most widely used correlation is one developed by Black (8) based on Angstrom's correlation with regression coefficients of 0.28 and 0.47 generalized for the tropical belt $0^0 – 60^0$ N & S.

However, once again the long term measurement of daily sunshine duration accurately is a costly exercise requiring skilled labor, rendering it impractical for many remote locations. In Sri Lanka, several radiation correlations have been employed but a general radiation model which can be considered reliable for estimation of solar energy for the three climatic zones (wet, dry and intermediate) does not exist. As the incident terrestrial solar irradiation at a given location varying with geometrical parameters (such as latitude and altitude) and meteorological parameters (sunshine duration, relative humidity, ambient temperature and cloud cover amount), an approximate generalized model has to be selected from models developed for similar climatic conditions and validated for Sri Lanka identifying the parameters which most impact the outcome. It is also important to identify a model which will rely on easily obtainable data without using complex instrumentation and the resultant inaccuracies that can arise in measurements. As cloud cover and atmospheric turbidity having a major impact than the latitudinal effect on the incident solar radiation in the tropics, it is appropriate to develop clearness index K_T based on sky conditions with the overcast and clear skies in the extremes (Bindi) (6). As rainfall is closely related to cloud cover in warm and humid tropical weather, this study attempts to develop a methodology to relate rainfall to incident solar radiation for a given location.

2. Correlations based on cloud cover data

The solar radiation that arrives at ground depends on the day of the year, the latitude of the location and on the atmospheric transmittance, also termed as the clearness index K_T. On reaching the earth's surface, the incoming radiation is partly reflected and partly absorbed. Net radiation, corresponding to the overall balance of absorbed solar radiation and long-wave exchange, is converted to the sum of sensible heat, latent heat and ground heat fluxes. During day time the earth's surface receives irradiative energy and both air and soil temperatures are expected to increase. At night, the surface loses energy by emitting radiation, especially during clear sky conditions. Hence, a clear day is expected to be generally characterized by an increased difference between night and day temperatures. On overcast days, the cloudiness reduces the incoming radiation during day time and also reduces the outgoing radiation at night. The difference between night and day temperatures is therefore expected to be reduced. Accordingly, the difference between the thermal ranges of two consecutive days is expected to be related to the difference in the mean sky transmittance (mean value for K_T) of the same two days (Bindi) (6). However, in the tropical countries this phenomenon is not so profound due to frequent convective cloud movements trapping heat into the atmosphere making the temperature differences between night and day minimal. Therefore, a closer relationship between solar radiation and cloud cover exists in the tropics.

As the cloud formation over tropical islands with a relatively small land mass is limited, most of the rain events occur from low pressure atmospheric conditions in the surrounding ocean. It is also observed that most of the rain events in Sri Lanka occur from Low-family clouds (Nimbostratus and Altostratus) and therefore it can be assumed that rain events (rainfall > 0.3 mm per day) in tropical islands occur on overcast days. Conversely non-rainy days can be assumed to be clear sky days. Further, research conducted in Pnom Penn in tropical Asia (Bindi) (6) has shown that the difference in incident solar radiation on rainy and clear days is lower than in high latitude countries. This fact is strengthened by the low difference of night and day time temperatures in the tropics.

2.1 Predicting mean sky transmittance of clear days $(K_T)_C$

The solar radiation that reaches the earth's surface on a clear day is a function of the solar constant, of the sine of the solar elevation, the relative air mass and the turbidity factor of the air mass. Turbidity, in turn, depends on the transmittance due to molecular scatter (Rayleigh), to ozone absorption, to the uniformly mixed gases, to water vapor and to aerosols (Justus and Paris) (3).

If a constant air pressure of 1013 hPa at 0 m elevation is assumed, the relative air mass is approximately calculated for given location, day of the year and time of day as the reciprocal of the sine of solar height. The turbidity factor (*TI*) is normally calculated from measured incoming radiation by means of Linke's method but it can be also estimated on the basis of an existing correlation between the water content of the atmosphere, i.e. its perceptible water (w), and the turbidity coefficient (β) by means of the empirical equation developed by Dogniaux and Lemoine (18)

$$TI = \{(\alpha+85)/(39.5e^{-w} + 47.4) + 0.1\} + (16 + 0.22w)\,\beta \qquad (1)$$

Where α = solar elevation (in degrees)

In absence of direct observations, the parameters w and β of equation 1 can be derived from the following classification of different types of radiation climates by neglecting the effect on these values of air mass conditions:

- polar and desert climates (dry air)	w = 0.5 to 1
- temperate climates	w = 2 to 4
- tropical climates (humid air)	w = 5
- rural site	β = 0.05
- urban site	β = 0.1
- industrial site	β = 0.2

(Dogniaux and Lemoine) (18)

When the value of *TI* is estimated for a given location for a given day of the year and for a given solar elevation, the sky transmittance of a clear sky $(K_T)_C$ is calculated, according to the modified Beer's law equation (Kasten & Czeplak) (33):

$$(K_T)_{Ch} = 0.83e^{(-0.026TI/\sin h)} \quad (2)$$

Where $(K_T)_{Ch}$ is the sky transmittance calculated for the solar elevation h. The mean daily values of $(K_T)_C$ can be found by integrating and averaging $(K_T)_{Ch}$ over the length of the day.

2.2 Predicting mean sky transmittance of overcast days $(K_T)_O$

The sky transmittance on an overcast day mainly depends on the thickness and type of clouds and on the sun elevation (Lumb) (40). It is known that high, middle and low clouds attenuate the solar radiation in different ways (Haurwitz (24), Bennet (5), Kimura and Stephenson (35)). A distinction between the fraction of total sky cover (TSC), often recorded in synoptic weather stations, and the fraction of cloud cover (cc), that takes into account the attenuation effect different cloud type groups, was made by Turner & Abdullaziz (65). The relationship between these two fractions is given as:

cc = TSC for low clouds, middle clouds or low and middle clouds
cc = 0.5 TSC for high clouds
cc = TSC – 0.5(Amount of high clouds) for mixed clouds

Since the model developed sets the condition that the overcast days are also rainy days, the rainfall probability of a given day is to some extent related to the cloud type being maximum for Low-Family clouds (Nimbostratus and Stratocumulus) for Middle clouds (Altocumulus and Altostratus) and for Vertical clouds (Cumulus and Cumulonimbus). Hence, the cloud cover fraction (cc) on days selected as overcast by the model is assumed to be equal to the maximum sky cover fraction (cc = 1)

Turner & Abdulaziz (65) developed an empirical equation to calculate the sky transmittance of overcast days as a function of the solar elevation and the cloud cover fraction. The equation has the following form:

$$(K_T)_{Oh} = a + b(cc)^2 \mathrm{Sinh} + c\,(cc)^2 + d\mathrm{Sinh} \quad (3)$$

Where, $(K_T)_{Oh}$ is the sky transmittance of an overcast day calculated for the solar elevation h and a, b, c and d are regression coefficients calculated for different solar elevation (Table 1). The value of the mean daily sky transmittance $(K_T)_O$ is calculated by integrating over the day and averaging.

Table 1: *Regression for different solar heights*

Range of α	*a*	*b*	*c*	d
$0^0 \le \alpha \le 20^0$	0.3080	-1.165	-0.0586	1.0743
$20^0 \le \alpha \le 40^0$	0.5695	-0.1065	-0.4755	0.2809
$40^0 \le \alpha \le 60^0$	0.7862	0.2736	-0.6943	-0.0467
$\alpha > 60^0$	0.6423	0.9109	-1.2873	0.1222

3. Methodology and Calculations

In this study, Sri Lanka is taken as representing a tropical country and daily rainfall data are collected at four locations in close proximity to weather stations. Locations are selected to represent the main climatic characteristics of the country with Colombo representing the coastal wet region, Nuwara Eliya the high altitude wet region, Anuradhapura and Hambantota representing the dry region. The monthly average daily radiation values for each location are obtained from SWERA TMY data base, calculated from direct measurement of solar irradiance, adjusted for system inaccuracies through the use of correlations based on weather parameters.

The clearness indexes for clear and overcast days are calculated as follows;

From equations 1 to 3 and taking w = 5 representing the tropical humid conditions and β = 0.1 to represent the urban nature of the weather station location clearness index for a clear day $(K_T)_C$ is calculated to be 0.68. Taking cc = 1 for low and middle clouds which are the most prevalent and rain causing in Sri Lanka, clearness index for an overcast day $(K_T)_O$ is calculated to be 0.28. The clearness index, K_T was calculated using equations 1, 2 and 3 for all locations using rainfall data where a rainy day is considered when rainfall in 24 hours is greater than 0.3 mm. Using the calculated clearness index values for overcast and clear days the monthly average daily solar radiation for a particular month can be obtained by calculating K_T by simply averaging corresponding clearness index values for rainy and non rainy days for the respective month. However, it can be seen that much accurate predictions can be made if the data on the number of rainy days per month can be calculated over a period of minimum 5 years. Chart 1 to 4 show monthly averaged daily values of incident solar radiation G_{m-h} calculated with monthly average K_T values (RF model) averaged over 5 years against monthly average daily solar radiation values from SWERA TMY data for the four stations. The Charts also show the G_{m-h} for K_T values calculated using RF model with data obtained during a single year (2008).

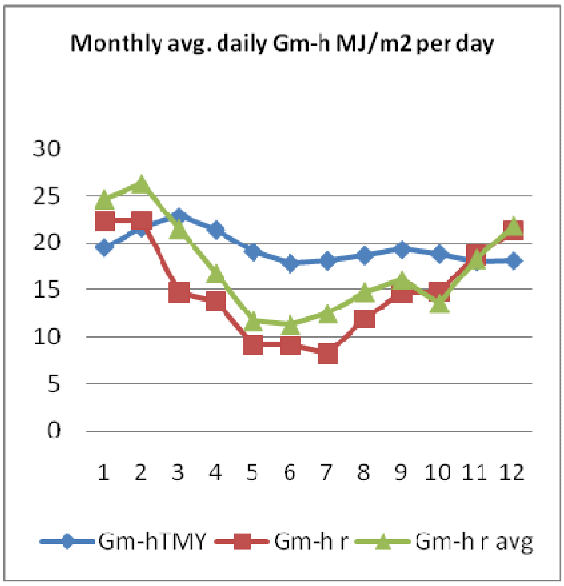

Chart 1: *Comparison of GSR(RF), Col.*

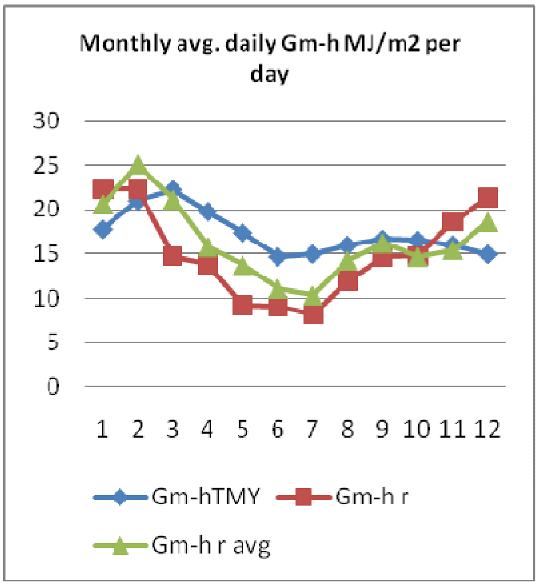

Chart 2: *Comparison of GSR(RF), NE.*

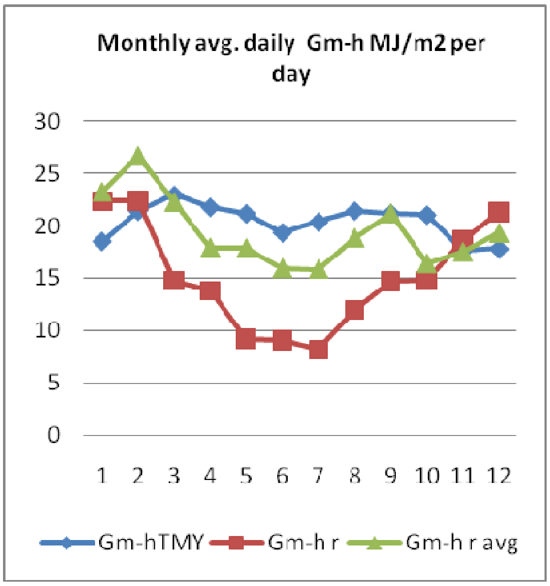

Chart 3: *Comparison of GSR(RF), A'pura*

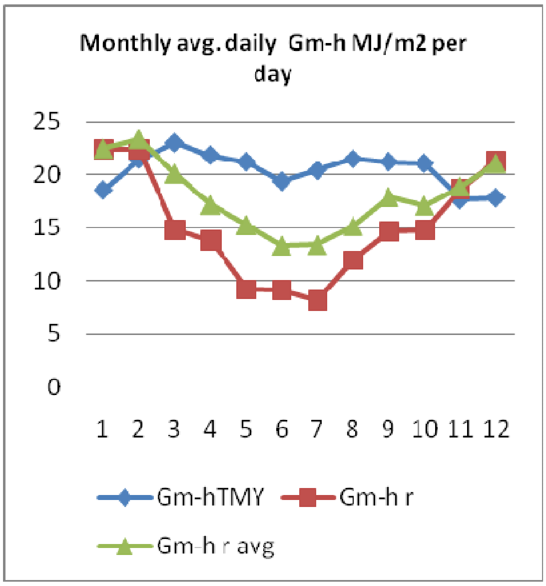

Chart 4: *Comparison of GSR(RF), H'tota*

In the Charts 1 to 4 $G_{m\text{-}h}$TMY, $G_{m\text{-}h}$ r and $G_{m\text{-}h}$ r avg denotes the monthly average daily global radiation on a horizontal surface obtained from SWERA TMY data base, average rainfall data for one year (RF model) and 5 rainfall data averaged over a period of 5 years (ARF model).

Table 2: *Percentage deviation of Gm-h (ARF) from corresponding SWERA TMY data*

Station	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Colombo	-26.1	-21.3	5.9	21.8	38.6	36.5	30.8	20.7	16.7	27.9	-1.4	-20.7
N'Eliya	-15.9	-19.4	5.0	20.2	20.9	24.5	30.9	10.7	2.6	11.2	3.6	-24.1
A'pura	-25.2	-24.3	3.14	17.9	15.8	17.7	22.2	12.2	0.18	22.1	0.92	-8.2
H'tota	-8.3	1.48	15.1	20.5	27.0	30.0	32.3	29.2	18.4	17.8	-1.4	-10.4

Charts 6 and 7 show the monthly average daily global radiation for the four locations obtained from SWERA data and ARF model indicating that in both cases sites located in the wet region displaying lower radiation levels after the end of the North- East monsoon period, i.e. from March to October.

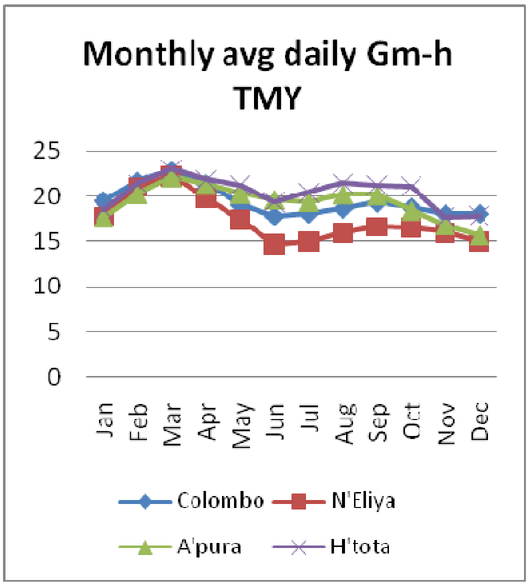

Chart 6: *Gm-h (SWERA) for all locations*

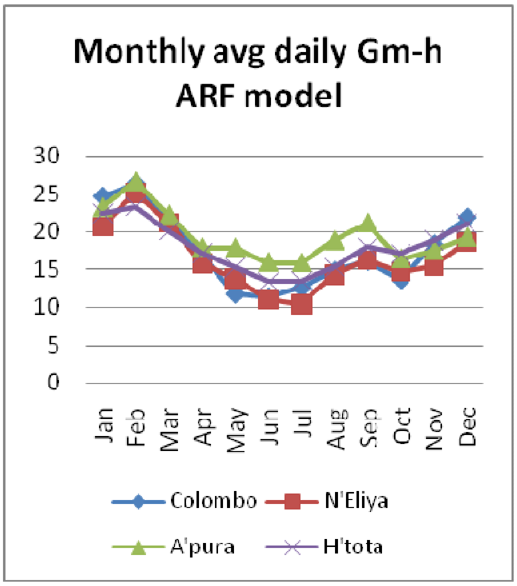

Chart 7: *Gm-h (ARF) for all locations*

4. Discussion

It can be seen from Table 2 that the percentage deviation of solar radiation values obtained through rainfall data from that of SWERA data are displaying a similar pattern over a calendar year for all four locations. Further, from Charts 1-4, it can be seen that the solar radiation values obtained through average rainfall (ARF) are more compatible with SWERA data, indicating the importance of collecting rainfall data over a longer period of time for more accuracy. However, as the shape of the graphs obtained for solar radiation values through ARF model for all four locations show consistency, it is reasonable to assume that the particular shape is due more to the amount and duration of rainfall and thus should be compatible with the type and extent of cloud cover observed.

The model can be further improved by closely examining the cloud formation patterns, wind directions and seasonal variations of weather in Sri Lanka. Though Sri Lanka is located close to the equator, as a country located in the northern- hemisphere it still experiences summer and wintry conditions albeit mildly. As such from December to February the day length is 3% shorter than the average of 12 hours and humidity is relatively low leading to higher percentage of high clouds formation in the cooler upper atmosphere. These high clouds, though mostly producing no rain or insignificant rainfall as trace precipitations or rain events less than 1 mm, still prevent significant amount of solar radiation penetration particularly during morning hours. Therefore when calculating the number of days in which rainfall events occur for the RF model, trace precipitation events as well as the rainfall events less than 1mm should also be taken into account during December – February period. The summer period from June to August on the other hand is 3% longer in day length from the average and the south-westerly wind with high humidity forms a higher percentage of isolated low and middle clouds, though causing minor rain events not blocking solar penetration for a prolonged period of time. Therefore, when the rain event is less than 1 mm per day, such days can be generally considered as clear days with considerable accuracy. As such, during the period from June to August only the days that produce more than 1mm of rain per day can be counted as rainy days for the RF model. For the in-between seasons precipitations more than 0.3 mm per day can be considered as rain events.

Further, as Sri Lanka is an island in the tropics, it is observed that more than 50% of the rain events during March to October occuring in the night time due to increased ground temperatures and the resultant wind direction from ocean the to inland, causing more rain events in the night and early morning. Therefore a considerable improvement in the RF model can be envisage if only the day time rain events are considered. A further improvement can be envisaged if the adjusted RF model can be provided with data from a longer historical time series of 5 or 10 years of day time rain events.

In the calculations, K_T values are taken at either overcast or clear sky conditions. However, there exist days where the cloud cover is partial or prevailing for a particular period of time during the day, necessitating in-between values for K_T using an interpolative technique. If such an interpolative method can be developed to define K_T values for days in between clear and overcast days, the variations from measured radiation data can be minimized enabling the ARF method to be widely used.

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