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PREDICTING SOLAR RADIATION FOR TROPICAL ISLANDS FROM RAINFALL DATA

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Abstract: There are many correlations developed to predict incident solar radiation at a given location developed based on geographical and meteorological parameters. However, all correlations depend on accurate measurement and availability of weather data such as sunshine duration, cloud cover, relative humidity, maximum and minimum temperatures etc, which essentially is a costly exercise in terms of equipment and labour. Sri Lanka being a tropical island of latitudinal change of only 30 along the length of the country, the meteorological factors govern the amount of incident radiation. Considering the cloud formation and wind patterns over Sri Lanka as well as the seasonal rainfall patterns, it can be observed that the mean number of rainy days can be used to predict the monthly average daily global radiation which can be used for calculations in solar related activities conveniently.

Keywords: Sunshine Duration, Clearness Index, Cloud Cover, Solar Radiation, Rainfall

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INTRODUCTION

Hargreaves-Samani (1985) is generally accepted for predicting incident global solar radiation levels in Sri Lanka. However, since the empirical coefficient $(K_T)'$ in Hargreaves-Samani model is fully dependent on the temperature difference it is worthwhile to explore the relationship between rainfall and the clearness index (K_T) which represents the percentage deflection by the sky of the incoming global solar radiation as the temperature difference is related to cloud cover (Bindi *et al.*, 1988)

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 *et al.*, 1988).

As the convective cloud formation over tropical islands with a relatively small land cover 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 in tropical Asia has shown that the difference in incident solar radiation on rainy and clear days is lower than in high latitude countries (Maracchi, 1988). This fact is strengthened by the low difference of night and day time temperatures in the tropics.

Many correlations are used to predict incident solar radiation using weather parameters such as sunshine duration and temperature difference related to cloud cover, but the high cost and low accuracy of measurement has limited the practice to a few weather stations. However, due to the high atmospheric humidity levels, the possibility of rain events when overcast conditions prevail is high in tropical countries. As such, it is worthwhile to explore the possibility of calculating a value for K_T based on the number of rainy days and use it to predict the incident solar radiation which could be used as a low cost technique.

OBJECTIVE

The objective of this paper is to establish a relationship between the monthly average daily global radiation and the mean number of rainy days experienced at a given location in order to estimate incident solar radiation cost effectively and conveniently.

REVIEW OF THEORIES

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 vapour and to aerosols (Justus and Paris 1985).

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 (1976).

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

where h = solar elevation (in degrees).

In absence of direct observations, the parameters w and β of **Eq. (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 (Dogniaux and Lemoine, 1982):

- 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

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, 1980).

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

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.

Predicting mean sky transmittance of overcast days $(KT)_O$

The sky transmittance on an overcast day mainly depends on the thickness and type of clouds and on the sun elevation (Lumb, 1964; Tabata, 1964). It is known that high, middle and low clouds attenuate the solar radiation in different ways (Haurwitz, 1948; Bennet, 1969, Kimura and Stephenson 1969). 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 of different cloud type groups, was made by Turner & Abdullaziz (1984). 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 and Abdulaziz (1984) 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:

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

where $(K_T)_{Oh}$ is the sky transmittance of an overcast day calculated for the solar elevation h, 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 h	*a*	*B*	*c*	**d**
$0° \le h \le 20°$	0.3080	-1.165	-0.0586	1.0743
$20° \le h \le 40°$	0.5695	-0.1065	-0.4755	0.2809
$40° \le h \le 60°$	0.7862	0.2736	-0.6943	-0.0467
$h > 60°$	0.6423	0.9109	-1.2873	0.1222

CALCULATION MECHANISM

Daily sunshine duration data and 3 hourly rainfall data are obtained from the Meteorological Department of Sri Lanka for four locations, Colombo (6° 54′ N, 79°51′ E, H = 10 m), Nuwara Eliya (6°50′ N, 80°50′ E, H = 1500 m), Anuradhapura (8°20′ N, 80°25′ E. H = 25 m) and Hambantota (6°10′ N, 81°15′ E, H = 8 m) representing the Wet zone, Central Hills, Intermediate and the Dry zones respectively. The zones are differentiated by the amount of rainfall each receives annually with the wet zone receiving over 2500 mm/year, intermediate zone receiving 1000 mm to 2500 mm per year while the dry zone receiving less than 1000 mm/year (Meteorological Department of Sri Lanka). The Central Hills can be grouped together with the wet zone where the precipitation levels are high at altitudes over 750 m.

Taking w = 5 representing the tropical humid conditions and $\beta = 0.1$ 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 Angtrom's (1924) correlation, which is the most commonly used correlation to predict solar radiation in Sri Lanka, for comparison of results is used with correlation constants developed for Visakhapatnam (Latitude 10° Longitude 74° E) in South India mainly due to geographical similarities in the absence of correlation constants developed for Sri Lanka.

VALIDATION

Figures 1–4 show typical meteorological year monthly average daily incident solar radiation for the four stations compared with the corresponding values from Angstrom's and Bindi *et al.* (1988) models. From the **Figures 1–4** and statistical parameters it can be inferred that Bindi *et al.* (1988) model is more closely compatible with Angstrom's model in the intermediate

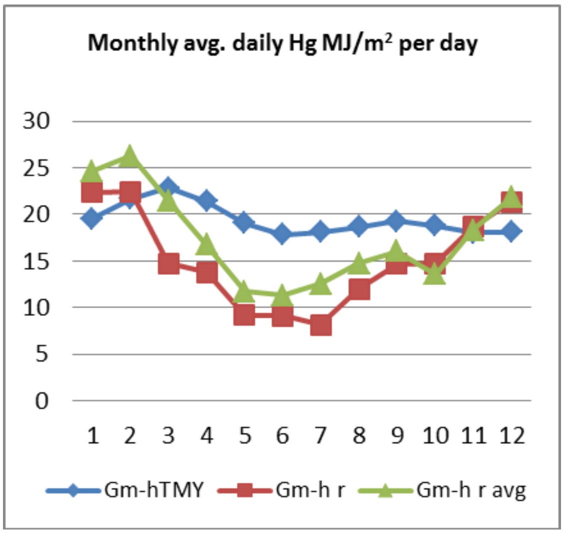

Fig. 1: Global radiation for Colombo.

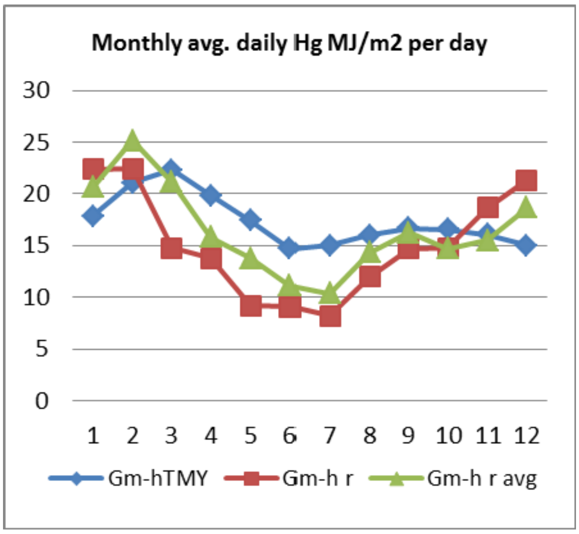

Fig. 2: Global radiation for Nuwara Eliya.

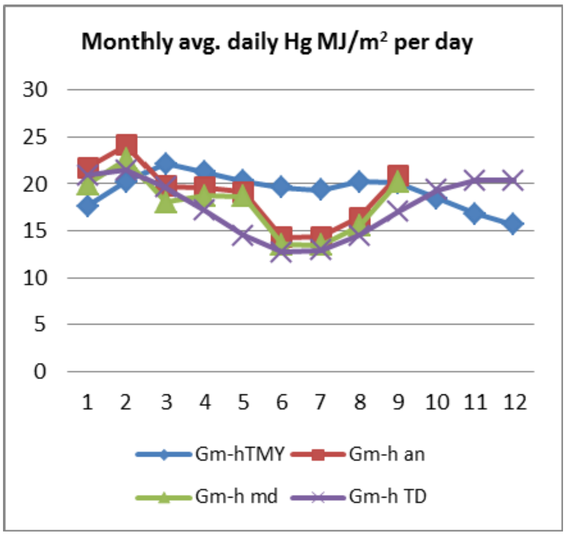

Fig. 3 Global radiation for Anuradhapura.

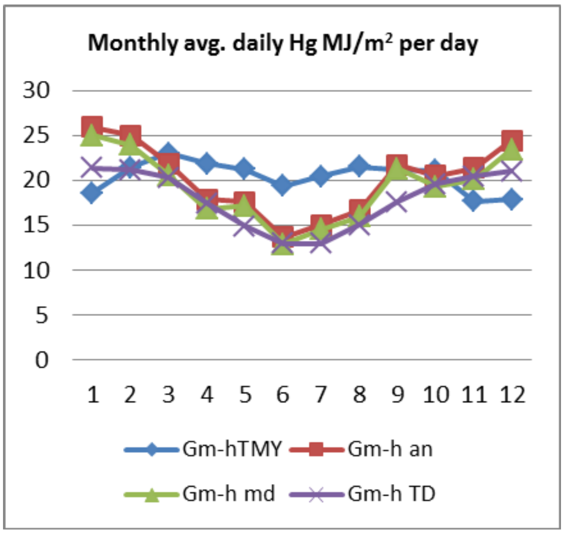

Fig. 4 Global radiation for Hambantota.

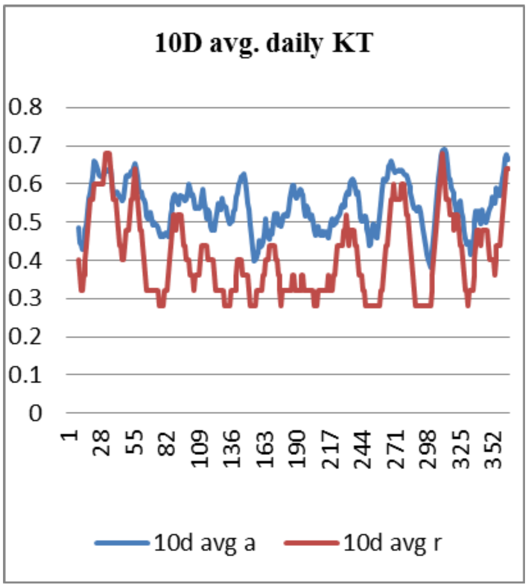

Fig. 5 10 day avg K_T for Colombo.

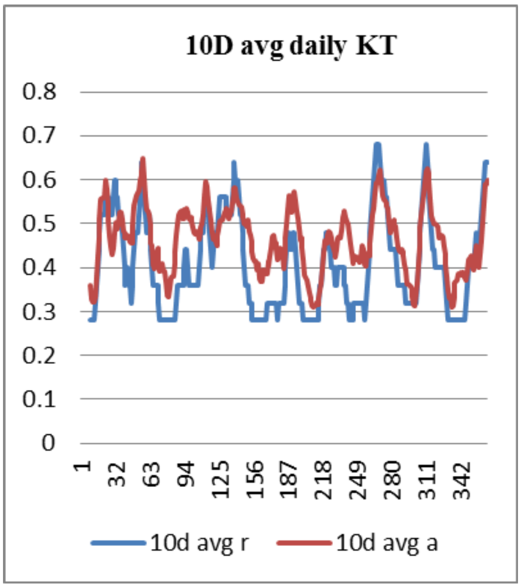

Fig. 6 10 day avg K_T for Nuwara Eliya.

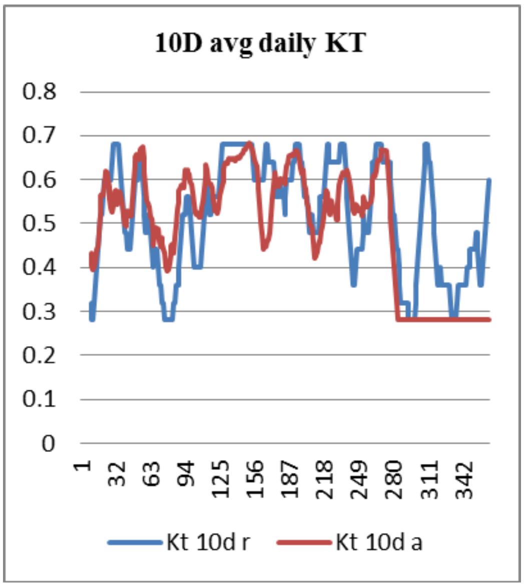

Fig. 7 10 day avg K_T for Anuradhapura.

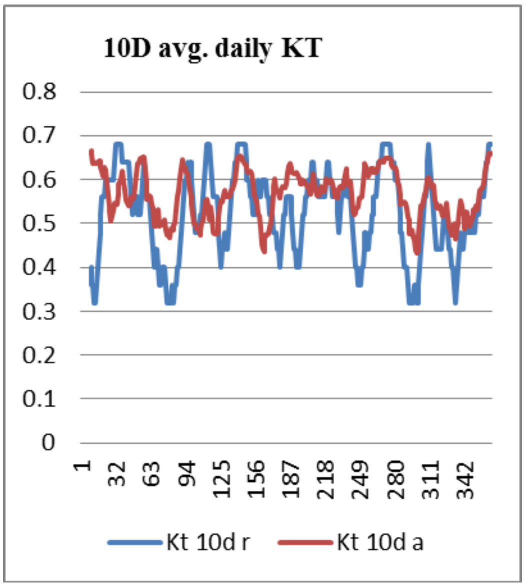

Fig. 8 10 day avg K_T for Hambantota.

Table 3. Percentage deviation of Gm-h (ARF) from corresponding 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	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	30	32.3	29.2	18.4	17.8	-1.4	-10.4

and dry zones where the rainfall is seasonal and the distinction between clear and overcast days are more pronounced. Since the wet and the high altitude regions experience cloudy but non rainy days in between clear and overcast days, a longer time series of data is required to accommodate the K_T values between the two extremes. The importance of such is depicted in **Figures 5–8** where 10 day moving average values for clearness index values calculated from the two models are plotted for all four stations.

Therefore, it can be concluded that Bindi (1984) model can be employed for any location in Sri Lanka where 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 no rainy days for the respective month over a time span of 5 years or more. **Figures 9–12** show monthly averaged daily values of incident solar radiation calculated with monthly average K_T values (Bindi, 1984) averaged over 5 years against monthly average daily solar radiation values from TMY data for the four stations.

Figures 9–12 clearly demonstrate that when a longer time span is used to calculate the average number of rainy days the increase in compatibility with corresponding TMY data. **Table 2** shows that global radiation values obtained from the Average Rainfall Model (ARF) model displaying close compatibility with the corresponding values obtained from the Angstroms model. The statistical parameters Root Mean Square Error (RMSE) and Mean Biased Error (MBE) between the values obtained from the two correlations clearly show that the values from ARF model can be used in place of Angstrom model.

Table 2. Statistical errors of Angstrom and ARF model compared with TMY

Region	Correlation	RMSE	MBE
Colombo	Angstr	52.03	0.12
	ARF	76.59	2.01
N'Eliya	Angstr	32.26	0.83
	ARF	31.69	0.92
A'pura	Angstr	31.97	0.89
	ARF	39.52	-0.09
H'tota	Angstr	69.31	0.33
	ARF	63.33	1.39

The percentage variation of global radiation calculated from the average rain fall (ARF) model from the corresponding TMY data are shown in **Table 3**. It is clear that a distinctive pattern exists for individual locations but generalization of the pattern into a broader region is not possible.

Figures 13–14 shows the monthly average daily global radiation for the four locations obtained from TMY data and ARF model indicating that in both cases sites located in the wet region displaying lower radiation levels after the North- East monsoon period, i.e. from March to October. This phenomenon is due to the distinctive nature of the North-East monsoon where rainfall is primarily from low and middle cloud formations due to low pressure systems in the Bay of

Bengal. The winds also blow from the North across the Indian sub-continent land mass causing very little or no rain. As a result historically there are more clear days in the N-E monsoon compared to the South-West (S-W) monsoon where the rain causing clouds are moving in from the south-Western direction across vast expanse of ocean and the days are cloudier with frequent rainy and overcast days. As such, the sites located in the dry region which depend primarily on the N-E monsoon for rain receives more solar radiation than the sites in the wet region.

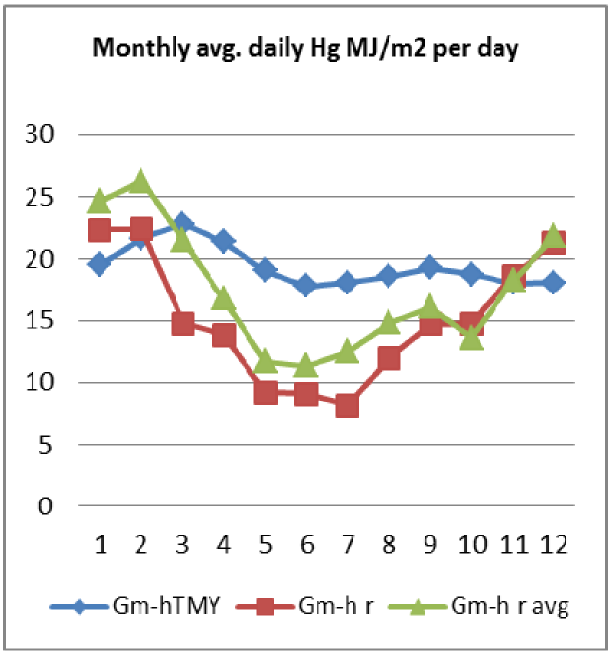

Fig. 9 Global radiation for Colombo.

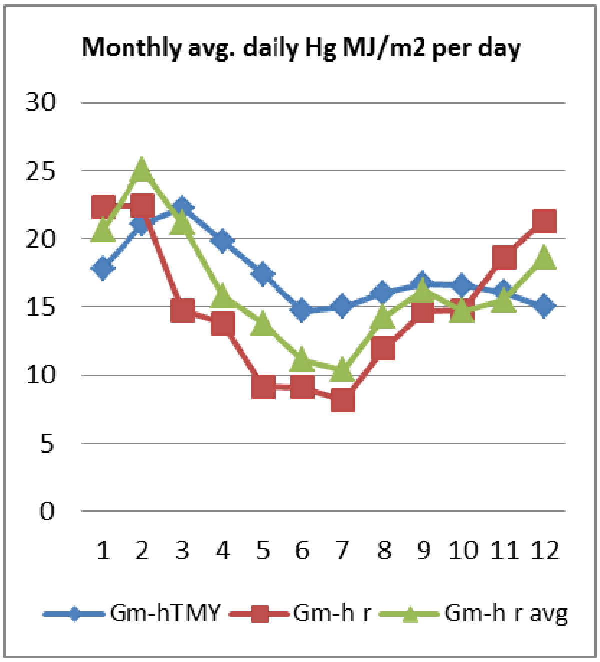

Fig. 10 Global radiation for Nueara Eliya.

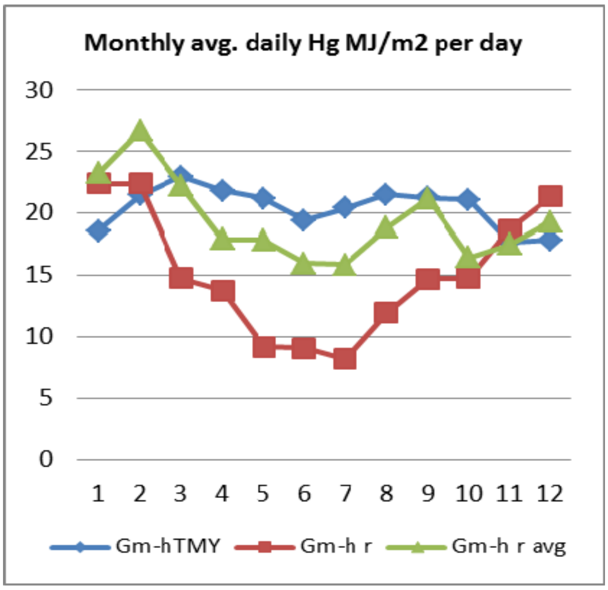

Fig. 11 Global radiation for Anuradhapura.

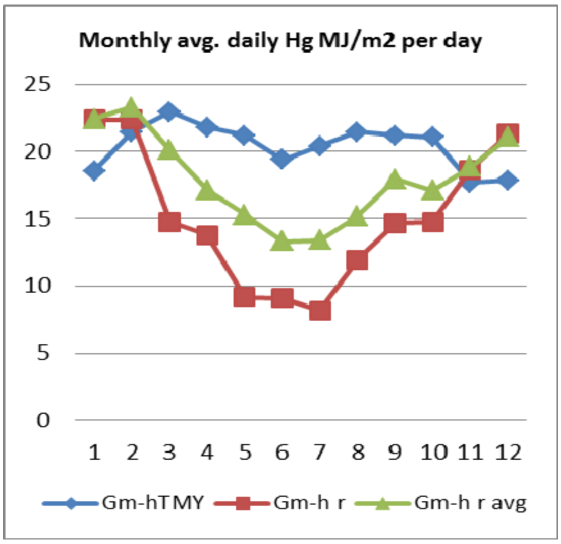

Fig. 12 Global radiation for Hambantota.

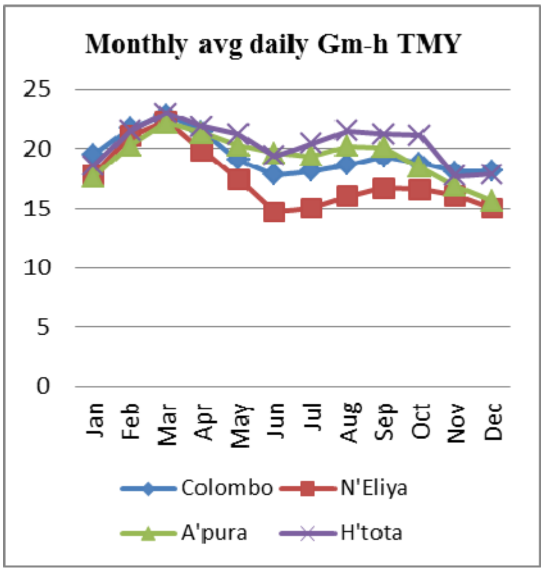

Fig. 13 Gm-h TMY for all locations.

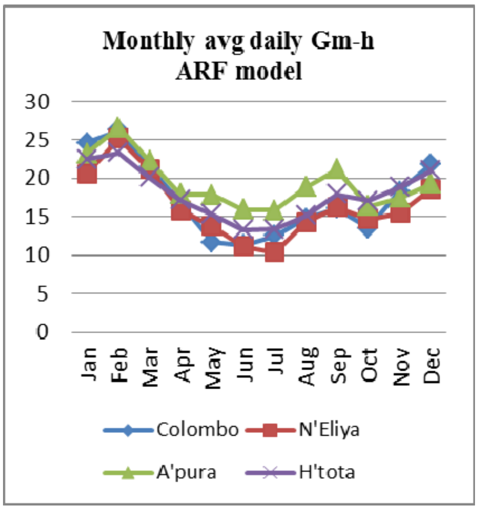

Fig. 14 Gm-h ARF for all locations.

It is also observed that the solar radiation values for sites in the wet region, except the locations in the central hills, are higher than that of sites in the dry region during the N-E monsoon.

This is due to the rain clouds losing their potential for rain when moving across the semi-arid North-Central plains in to the wet region. Further, when the rain clouds in the N-E monsoon crosses over to the wet region of Sri Lanka the potential for rain is greatly diminished as a result of clouds moving over semi-arid North-Central plains. As such the landmass of Sri Lanka could be broadly demarcated into two regions where the area encompassing the South-West and the Central hills which receive over 2500 mm of rain annually and the combination of the intermediate zone and the dry zone receiving less than 2500 mm of rain per year defined as the dry region.

Figures 15–16 depicts the mean monthly average daily global radiation values for the wet and dry regions obtained using TMY and ARF model data. **Table 4** shows the percentage variation of mean monthly average daily global radiation values for the wet and dry regions obtained from ARF model with the corresponding values of TMY data which clearly show that a distinctive generalized pattern can be established.

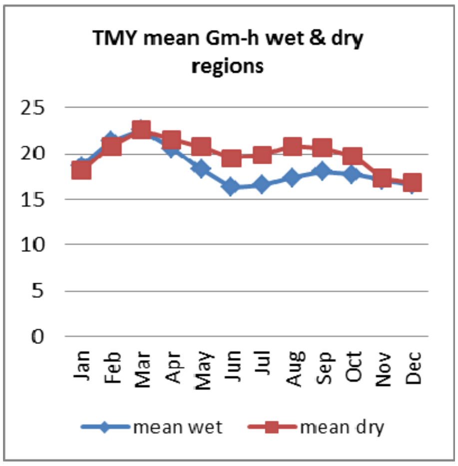

Fig. 15 Gm-h mean TMY for all locations.

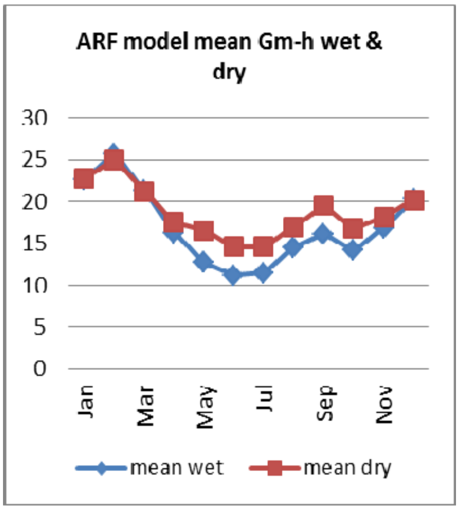

Fig. 16 Gm-h mean ARF for all locations.

DISCUSSION AND RECOMMENDATIONS

In the absence of a suitable correlation to predict incident global radiation at a given location TMY data developed through satellite technology and certain ground measured data are used in PV and other solar related technological calculations. However, TMY data are available only for a limited number of locations and the fact that radiation data cannot be accurately interpolated over a distance more than 50 Km requires numerical predictive models to ascertain solar radiation values. While Angtrom's correlation can be generally used with correlation constants developed for similar Indian locations, the unique geographical and weather pattern particular to a tropical island nation like Sri Lanka need a more localized correlation with clearly quantified variations from TMY data. It is also necessary to be able to predict solar radiation levels using widely available and short term data so that calculations can be cost effectively carried out and quick decisions can be made in designing.

From **Table 4** very distinctive and similarly distributed percentage variation pattern can be identified for both wet and dry regions. The ARF model under-estimates TMY data from April to October reaching maximum levels in June/July while over-estimating from November to February reaching minimum values in December-January. The under-estimation occurs due to considering all rainy days as overcast days where from April to October rain events occur more in isolation interspersed with sun. This is a direct result of convective low cloud formation in the southern Indian Ocean blown across at a higher speed from the South-West direction. The over-estimation during November to December occurs during the winter time for the northern hemisphere where non-rain forming high clouds prevail giving low values for K_T in TMY data where as in the ARF model such days are taken as clear sky days. As such an interpolative method to define K_T values for days in between clear and overcast days can be employed to minimize the variations.

Table 4. Percentage deviation of mean wet & dry values of Gm-h (ARF) from mean wet & dry values of TMY data

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet	-21.2	-20.4	5.5	21.0	30.1	31.1	30.8	16.1	10.2	20.1	0.9	-22.3
Dry	-26.2	-19.9	6.1	18.7	20.1	24.7	26.4	18.4	5.4	15.2	-5.4	-20.4

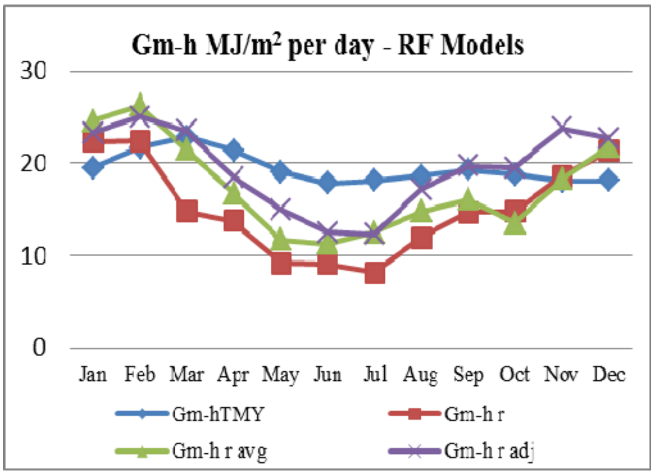

Fig. 17 Comparison of RF model outcomes with TMY data.

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 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 occurring in the night time due to increased ground temperatures and the resultant wind direction from ocean to the 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 as shown in **Fig. 17**. **Figure 17** shows the monthly average daily global radiation obtained from RF model with 24 hour rain events and non-adjusted for seasonal climate factors, ARF model with 5 year average rainy days with 24 hour rain events and non-adjusted for seasonal climate factors and the seasonally adjusted RF model with only the day time rain events counted compared with TMY data for Colombo.

It can be seen that the adjusted RF model displays the best compatibility with TMY data. 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.

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