ESTIMATING INCIDENT SOLAR RADIATION IN TROPICAL ISLANDS WITH SHORT TERM WEATHER DATA

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Abstract

Solar radiation incident on a particular location depends on geographical and meteorological factors and as such vary spatially as well as temporally. For any given solar radiation related application an accurate prediction of incident solar radiation is important. However due to high cost of measuring and recording, solar radiation data are confined generally to a few locations, for example in Sri Lanka it is confined only to the capital city, Colombo. As such, a correlation to predict incident solar radiation based on meteorological and geographical parameters will have to be identified and validated taking into account the climatic differences in tropical regions with localized variations. In addition, due to non-availability of accurate historical meteorological data, estimated percentage variations are identified which can be used to predict incident solar radiation at a given location when two broad climatic regions are defined.

Keywords: Incident solar radiation, weather data

Introduction

The ground surface solar radiation is an amalgamation of several layers that emit and absorb radiation of various wavelengths, and goes through different processes of assimilation and dispersion. Water droplets, dust and air molecules are the main cause of the dispersion while the absorption is due to ozone, oxygen, carbon dioxide, carbon monoxide, water vapors and nitrogen (Tiwari, 2002).

Accurate prediction of incident solar radiation at a given location is of great importance for any solar radiation based application or sizing models in Photovoltic (PV) power systems, building design applications and in agriculture. It is important for tropical developing countries such as Sri Lanka, where the annual average solar irradiation is in the range of 5.5 $kWhm^{-2}d^{-1}$ and available throughout the year with low seasonal variations, to actively pursue the production of renewable energy through PV technology in the light of massive expenditure on imported fossil fuel. In Sri Lanka, less than 30% of the total energy demand is met by the hydro power sources as at December 2008 (source: Central Bank of Sri Lanka). Since the energy demand is on the rise and most of the potential hydro-power sources are already tapped, any future increases have to be met with non-renewable petroleum.

Spatial interpolation techniques allow estimation of solar radiation at any given point from nearby stations records (Suckling 1985). The accuracy of this method depends on the mean grid size of the radiation measurement network and on the mean variability of weather conditions over the studied region. Weather variability may depend on many factors, especially the topography. Suckling (1985) studied the relationship between the extrapolation distance and the error in radiation estimates due to extrapolation for a large number of climatic regions. It is noted that in central Europe, mean absolute errors due to extrapolation are a linear function of the extrapolation distance and are normally greater than 2 $MJm^{-2}d^{-1}$ (Bindi, 1991).

The Meteorological Department of Sri Lanka measures global solar radiation only at the Colombo station (6^0 54’N, 79^0 51E, H=10 m) while sunshine data are recorded at four stations, namely, Colombo (Western Province), Nuwara Eliya ($6^0$50’N, $80^0$50’E, H=1500m) (Central Province), Anuradhapura ($8^0$20’N, $80^0$25’E. H=25m)(North-Central Province) and Hambantota ($6^0$10’N, $81^0$15’E, H=8m) (Southern Province) located in very different climatic regions where western province (WP) is humid and at low altitude, central Province (CP) is humid and at high altitude and North Central Province (NCP) and Southern Provinces (SP) are dry and at low altitudes. For a tropical island country (Latitude 6^0-9^0) with a land mass of approximately 65000 km^2, Sri Lanka is having wide variations in geographical features that estimating incident solar radiation using spatial interpolation techniques cannot be recommended for distances greater than 50 km from the weather station.

Standard meteorological observations have already been used to estimate solar radiation and models have been developed for this purpose. Some of these are based on empirical formulae (Atwater and Ball 1978 , Bristow and Campbell 1984 , Hodges et al. 1985 , Maracchi et al 1988 , McCaskill 1990) , while other models involve complex numerical calculations (Cengiz et al. 1981 , Richardson 1981). Parameters used as input include air temperature, degree-hours of temperature, relative humidity and rainfall. Historical data (mean annual daily solar radiation, amplitude of annual curves of daily solar radiation, etc.) and geographical data (inter-correlations between daily maximum and minimum temperatures and solar radiation at a geographical area) are also required.

Angstrom (1924) developed a linear correlation model, modified by Prescot (1940) using sunshine duration while Reddy (1971) and Sabbagh and Sayigh, (1977) have derived models by using sunshine duration, relative Humidity (RH), latitude and air temperatures of the location of interest. Kamberzidis et. Al. (1994) estimated the hourly and daily global and diffuse radiation from the Meteorological Radiation Model (MRM) developed at the National Observatory of Athens using meteorological data (air temperature, atmospheric pressure, RH and sunshine duration). Paltridge and Proctor (1976) employed cloud fraction (CF) and latitude in a model which was able to predict the direct and diffuse daily solar irradiation at the earth's surface while Mahamoud and Nather (2003), and Zhou and Yezheng (2005) employed only sunshine duration for predicting surface global radiation for different places in the world.

For any useful application of a correlation the input data required should be easily practically collected for a given location. Therefore, of the several correlations that have been developed, linear correlation between ratio of incident solar radiation to extra-terrestrial radiation and relative sunshine duration (Angstrom, 1924), quadratic regression equation model depicting the correlation between ratio of incident solar radiation to extra-terrestrial radiation and relative sunshine duration (Etuk, 1981) and the estimative equation where the ratio of incident solar radiation to extra-terrestrial radiation is related to the difference of the maximum and minimum air temperature for the location Hargreaves (1994) are considered in this research.

Nomenclature

S	Solar constant 0.0820 $MJm^{-2}min^{-1}$
S_d	Sunshine duration per day (hours)
S_{max}	Maximum sunshine duration per day (hours)
E_o	Extra-terrestrial solar radiation, $MJm^{-2}d^{-1}$
G_{d-h}	Daily Global radiation on a horizontal surface
D_{d-h}	Daily Diffuse radiation on a horizontal surface
n	Julian day ranging 1 (1st January) and 365 or 366 (31st December)
γ	Azimuth angle (east and west are positive, south is zero)
δ	Declination of the sun
α	Solar elevation angle above the horizon
θ	Zenith angle (complement angle to α)
φ	Geographical latitude
ψ	Azimuth angle of the sun (east is positive, west is negative)
ω	Hour angle of the sun (noon is 0, morning is negative, afternoon is positive)
RMSE	Root Mean Square Error
MBE	Mean Biased Error

Objective:

The objective of this study was to identify a generalized model for daily global radiation predictions in tropical islands, highlighting the most impacting parameters on the outcome.

Review of Theories:

- **Correlation 1 – Angstrom Method**

Angstrom (1924) suggested the basic equation [1] for the estimation of the total solar radiation which lately was further developed by Prescott (1940). In the equation the total solar radiation is linearly related to the amount of sunshine hours by the form,

$$G_{d-h} / E_o = a + b\{S_d / S_{max}\} \qquad [1]$$

The clearness index K_T ($=H_g / H_o$) represents the percentage deflection by the sky of the incoming global solar radiation and therefore indicates both the level of availability of solar radiation and changes in atmospheric conditions in a given locality, while relative sunshine S_R ($=S_d / S_{max}$) is a measure of the cloud cover. G_{d-h} represents the daily global radiation ($MJm^{-2}\ day^{-1}$) on a horizontal surface, E_o the daily extra-terrestrial radiation ($MJm^{-2}\ day^{-1}$), S_d the daily sunshine duration (hours) and S_{max} the maximum sunshine duration or day length (hours).

E_o can be calculated using equation

$$Eo = S\left\{1 + 0.33\,\mathrm{Cos}\,\frac{360n}{365}\right\}\int (Sin\phi Sin\delta + Cos\phi Cos\delta Cos\varpi)dt \qquad [2]$$

Where;

$$d_r = \left\{1 + 0.33\,\mathrm{Cos}\,\frac{360n}{365}\right\}$$

d_r is the inverse relative distance between earth and Sun

$$d_r = \frac{180S}{15\pi}\left\{1 + 0.33 \cos\frac{360n}{365}\right\}\int_{-\varpi s}^{+\varpi s}(Sin\phi Sin\,\delta + Cos\phi\, Cos\,\delta Cos\,\varpi)d\varpi$$

$$= \frac{24S}{\pi}\left\{1 + 0.33 \cos\frac{360n}{365}\right\}\left\{\varpi\, S Sin\,\phi Sin\delta + Cos\phi Cos\delta Sin\,\varpi\, S\right\}$$

The maximum possible sunshine duration S_{max} can be calculated as:

$$S_{max} = \frac{2\omega}{15} \qquad [3]$$

The equation [1] can also be written as

$$K_T = a + b\, S_R \qquad [4]$$

The constants **a** and **b** are empirical values and can be obtained from statistical considerations. The value of these constants depends on latitude, elevation above sea level, relative air humidity, maximum and minimum air temperature, relative sunshine duration and so on. The physical significance of the parameters **a** and **b** is that **a** is the measure of the overall atmospheric transmission for totally cloudy conditions, $S_d = 0$, and is a function of the type and thickness of the cloud cover, while **b** expresses the rate of increase of K_T with S_R. The sum (**a+b**) denotes the overall atmospheric transmission under clear sky conditions.

For Sri Lanka the values 0.28 and 0.47 are taken as the corresponding values for **a** and **b** which are the same for Visakhapatnam ($9^0$50'N, $79^0$25'E) in South India

Therefore,

$$K_T = 0.28 + 0.47\, S_R \qquad [5]$$

- **Correlation 2 – Akinoglu and Ecevit model**

Observing that the Angstrom-Prescott one-parameter model is, to a large extent, locality dependent, Akinoglu and Ecevit (1993) suggested a quadratic correlation between K_T and S_R to estimate the values of global solar radiation for 58 locations in several countries including tropical sites. The equation is given as

$$K_T = 0.145 + 0.845\, S_R - 0.280\, (S_R)^2 \qquad [6]$$

However, as subsequent research by Etuk and Akpabio and (2002) showed that the relationship between clearness index K_T and relative sunshine S_R in quadratic form is to some extent locality dependent. An equation developed for the city of Onne in tropical Nigeria (Latitude 3^0), where the meteorological parameters are similar to many locations in Sri Lanka is selected. Therefore the modified equation is given as;

$$K_T = 0.147 + 1.125\, S_R - 0.416\, (S_R)^2 \qquad [7]$$

- **Correlation 3 – Hargreaves-Samani equation**

Hargreaves and Samani have developed an equation to estimate solar radiation H_g, using only the dry bulb air temperature data at a location. The equation is given as

$G_{d\text{-}h} = H_o(KT)'(TD)^{0.5}$

i.e. $K_T = (KT)'(TD)^{0.5}$ [8]

Where TD = maximum daily temperature minus minimum daily temperature (^{0}C) for a given period and (K_T)' is an empirical constant.

Hargreaves (1994) recommended using $(K_T)'=0.162$ for interior regions and $(K_T)'=0.19$ for coastal regions. However, there is an implicit assumption in equation [8] which could result in significant errors in some conditions. Equation [8] assumes that the difference in maximum and minimum temperature is directly related to the fraction of extraterrestrial radiation received at the ground level. However, there are factors other than solar radiation, cloudiness and humidity that can influence the difference in maximum and minimum temperature in a given location. These factors include; latitude, elevation, topography, storm patterns, advection and proximity to a large body of water. For example, at low latitudes (tropical climates), the temperature difference becomes negligible and consequently equation [8] becomes insensitive and could significantly under estimate incident solar radiation as demonstrated by Jagtap(1991).

Knapp and Stoffel (1980) recommended a correction factor for $(K_T)'$ based on average monthly temperature and radiation data for a period of 25 years for the continental United States. Using average monthly data for the entire year, from 65 weather stations located between 7^0 to 50^0N latitude in United States, the following relationship was developed between TD and $(K_T)'$

$(KT)' = 0.00185(TD)^2 – 0.0433(TD) + 0.4023$ [9]

The relationship shows that $(K_T)'$ itself is a function of temperature difference. As temperature difference decreases, $(K_T)'$ changes from a low value of 0.13 to a high value of 0.24, a variation of as much as 85%.

Calculation Mechanism (Tropical island of Sri Lanka as a case study)

Applying the calculated daily extraterrestrial radiation H_0 and maximum daily sunshine duration S_0 in the three correlations, for given daily sunshine duration values and temperature difference values, the daily average global solar radiation can be found. Daily average global radiation, daily average sunshine duration and daily values of maximum and minimum air temperature are obtained from four weather stations of the meteorological department of Sri Lanka located at Colombo(WP), Nuwara Eliya (CP), Anuradhapura (NCP) and Hambantota (SP) for a duration of one year (from 1 January 2008 to 31 December 2008).

Plotting monthly average daily incident solar radiation for Colombo, Nuwara Eliya, Anuradhapura and Hambantota clearly shows that Angstrom’s linear correlation is better suited to predict solar radiation levels in different climates of Sri Lanka (Figure 1, Figure 2, Figure 3, Figure 4).

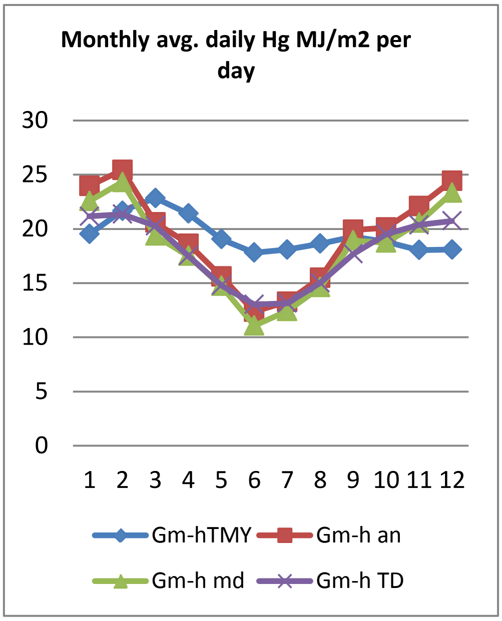

Figure 1: Global radiation-Colombo 2008

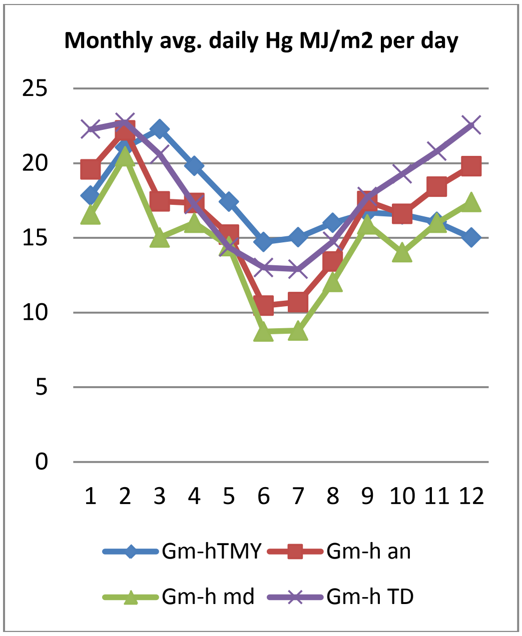

Figure 2: Global radiation- NuwaraEliya 2008

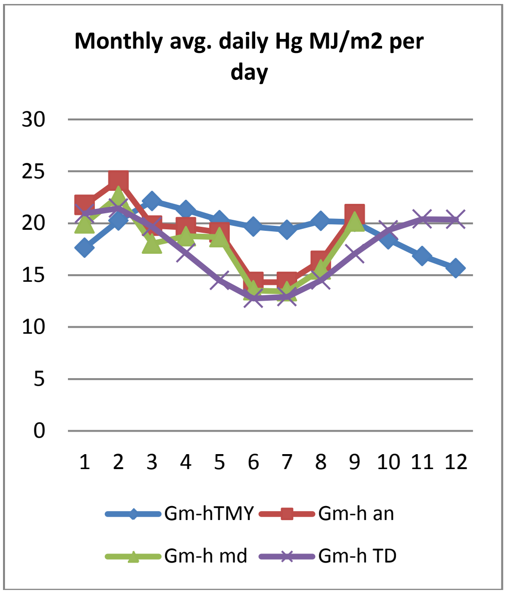

Figure 3: Global radiation-Anuradhapura 2008

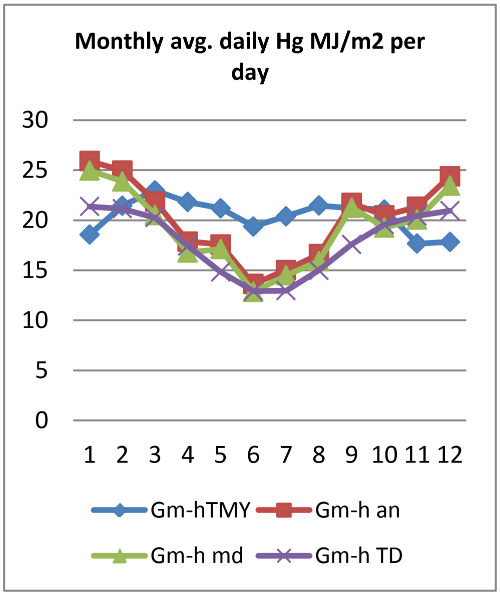

Figure 4: Global radiation- Hambantota 2008

Validation

Solar and Wind Energy Resources Authority (SWERA) under the United States Department of Energy has obtained monthly average daily radiation for six locations in Sri Lanka including Colombo, Nuwara Eliya, Anuradhapura and Hambantota using satellite technology as well as ground measurement of weather data. Comparing the calculated and the satellite data it can be seen that the results from correlation 1 provides predicted values of incident solar radiation closer to Typical Meteorological Year (TMY) data in all four locations.

The monthly average daily radiation calculated from the three correlations and the TMY monthly average daily radiation along with the statistical parameters RMSE and MBE are given in Table 1

Table 1: Statistical parameters for comparing radiation data with TMY data

Station	*RMSE Angstrom*	*RMSE Modified*	*RMSE TD*	*MBE Angstrom*	*MBE Modified*	*MBE TD*
Colombo	51.97	54.75	34.21	0.115	1.25	1.56
N’eliya	32.22	52.36	39.92	0.83	2.76	-0.81
A’pura	36.88	43.78	68.14	1.18	2.24	1.74
H’tota	56.59	61.35	68.50	0.85	1.67	2.81

It can be seen that Angstrom’s linear correlation (correlation 1), with the lowest error parameter values, is the most suitable correlation to be used to predict solar radiation in Sri Lanka.

Discussion and Recommendations

It can be seen from the charts 1 to 4 that the curve representing Angstroms equation with parameters developed for Visakhapatnam in South India generally follows the TMY curve for all four climatic regions in Sri Lanka. However, the percentage variation of incident radiation from TMY data (Table 2) indicate that in all four locations predictive figures over-estimate the TMY figures in the range of 5% to 30% from March to August while under-estimating by 1% to 40% from October to February. The minimum percentage variations in March-April and September-October, when the sun path crosses the equator, indicate that the variations are more likely due to meteorological factors rather than geographical factors.

Table 2: Percentage variation of predicted radiation from Angstrom model to TMY data

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Colombo	22.7	17.4	-9.9	-13	-18.1	-30.5	-26.6	-16.9	3.2	6.9	22.4	35
N'Eliya	9.8	5.4	-21.7	-12.6	-12.7	-28.9	-28.9	-16.3	4.6	0.2	14.6	31.8
A'pura	23.4	19.1	-10.7	-7.9	-5.7	-27.1	-25.9	-18.9	3.7	-	-	-
H'tota	39.6	16.4	-4.8	-18.1	-17.1	-29.7	-26.4	-22.6	2.4	2.8	20.8	36.7

As for a given location meteorological parameters vary temporally and it is important to simulate data over a considerable period of time (over 50 years or so) to identify seasonal patterns which could then be used to calculate climatic parameters such as the clearness index K_T. From Table 2 the percentage variations indicate a relationship to cloud cover over the regions considered over-estimating or under-estimating K_T when the declination angle is greater.

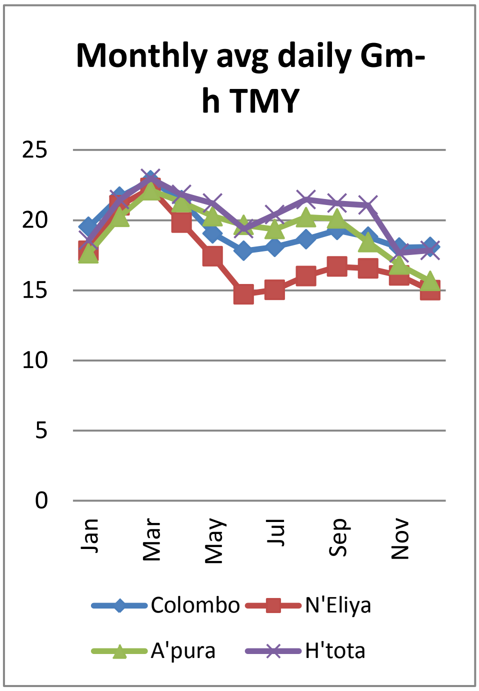

Figure 5: Radiation from TMY data

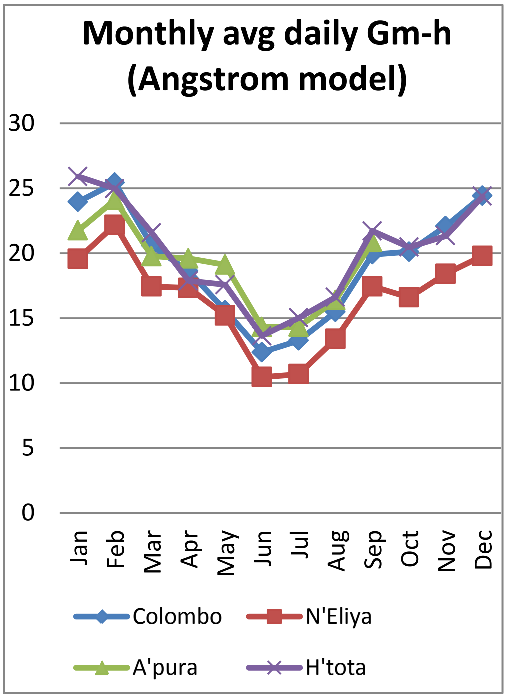

Figure 6: Radiation from Angstrom model

The Figure 5 and Figure 6 depict the monthly average daily incident global radiation on a horizontal surface obtained using data from TMY data set and from Angstrom's correlation. From the charts it can be clearly identified that the locations Colombo and Nuwara Eliya which are in the wet region of the country (annual rainfall over 2500 mm) with frequent cloud cover depressing the incident radiation more than that in the dry region (annual rainfall less than 2500 mm). As such mean radiation values are established in both TMY and Angtrom scenarios as shown in the Figure 7 and Figure 8

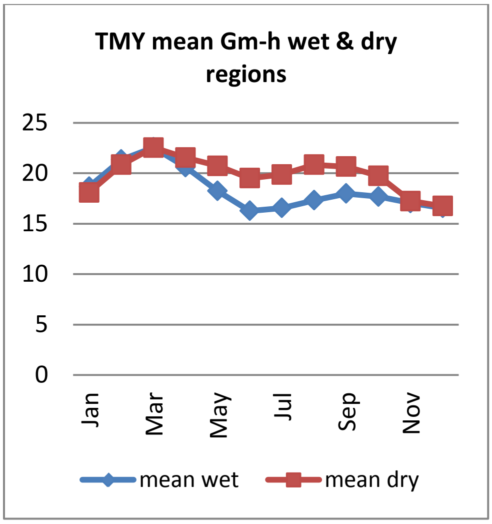

Figure 7: Radiation for wet and dry regions

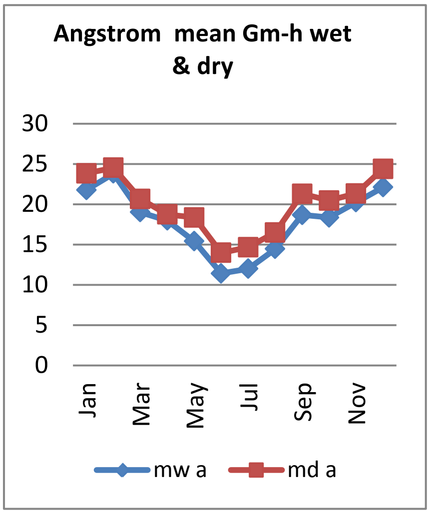

Figure 8: Radiation for wet and dryregions

Comparing TMY data for the wet and dry regions with the corresponding data from Angstrom model gives a clearer parallels as shown in Figure 9 and Figure 10

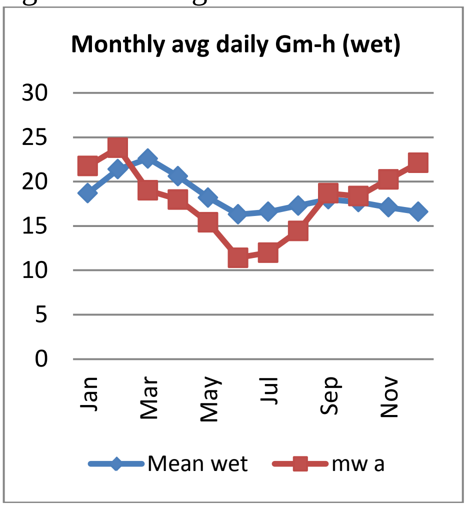

Figure 9: TMY (wet) against Angtrom (wet)

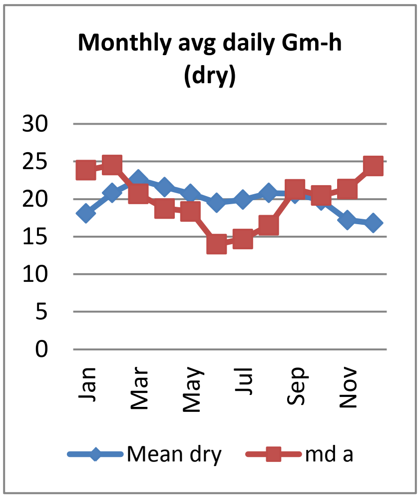

Figure 10: TMY (dry) against Angtrom (dry)

Table 3 depicts the percentage variation of incident solar radiation for the two regions compared with the corresponding mean TMY data.

Table 3: Percentage variation of mean radiation from Angstrom model to mean TMY data

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wet	16.4	11.3	15.9	12.7	15.3	29.9	27.8	16.5	3.8	3.7	18.4	33.2
Dry	31.7	17.9	-8.5	13.2	11.4	28.3	26.3	20.7	2.9	3.4	24	45.2

The two curves obtained from Angstrom correlation show consistency in variation with respect to TMY data. The near 30% under-estimated radiation values reflect the low K_T values calculated from Angstrom's correlation from March to August as the first inter-monsoonal rains (March to May) and south-west monsoons (June to September) set in and fast moving low and middle clouds interfering in the accuracy of recorded sunshine durations. Further, this period coincides with the summer time in the northern hemisphere and as such the day lengths are longer than that of during November to February. The over-estimation of radiation values from November to February could be attributed to a less cloudy period in an otherwise wet season in the dry region in 2008 emphasising the need to simulate data over a longer period of time. Shorter day lengths in the period could also increase the clearness index values marginally. The formation of high clouds, particularly in the mornings, due to lower humidity levels and cooler night time temperatures during December to February also contribute to the decreased intensity of solar radiation i'mpacting the accuracy of calculated radiation values using sunshine duration. This study therefore strengthens the argument that outcome from the Angstrom's correlation is location dependent and as such the need to define equation parameters developed through long term simulation of sunshine data particularly for regions of dissimilar climatic conditions.

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