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Alternative method for Estimation of Mean Monthly Diffuse Solar Radiation in Malawi

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ABSTRACT
Solar radiation measurements are taken at 25 locations in Malawi, a tropical country. Nevertheless, for a long time only Chileka weather station has been recording both global and diffuse radiation in the country. Consequently, there is need for use of empirical methods for estimating the mean monthly daily diffuse radiation (D) from the global radiation (H) and extraterrestrial radiation (H_0) on a horizontal plane. Daily global and diffuse solar radiation data was obtained from Chileka weather station. A linear regression analysis was performed on the computed values of the mean monthly daily clearness index $K = H/H_0$ and mean monthly diffuse fraction $R = D/H$. A linear correlation between K and R was formulated. The correlation was highly significant (p-value $= 0.00$, $r^2 = 0.83$) under the prevailing climatic conditions at Chileka, and it was used to estimate the mean monthly daily diffuse irradiance at another site.

1 INTRODUCTION

Knowledge about diffuse irradiance is required for the development of solar systems and other applications. Studies show that the efficiency of a solar collector decreases as the level of diffuse radiation rises (Ashrae, 1991). Diffuse irradiance is also used for monitoring atmospheric air pollution (Maudeukwe & Chendo, 1998), (Jacovides et al., 2000). However, a few stations measure the diffuse radiation although the global solar radiation on a horizontal surface is captured at many locations. Computational techniques are therefore used to estimate the diffuse component of solar radiation at many sites in the world. About 250 models and correlations to evaluate the diffuse component are found in literature (De Miguel et al., 2001). The choice of a specific model depends on several factors including availability of data, algorithms and numerical coefficients. In this study, two models are considered.(chosen based on the said factors?)

Page (1979) suggested a linear model for calculating the mean monthly daily diffuse radiation (D) from the mean monthly daily global radiation (H) and extraterrestrial radiation (H_o) on a horizontal surface. In this model, the clearness index $K = H/H_o$ is correlated with the diffuse fraction $R = D/H$:

$$R = a_0 + a_1 K \tag{1}$$

where a_0 and a_1 are coefficients.

Equation (1) is simple and can easily be fitted to data. Eleven years later, Coppolino (1990) proposed a non-linear formula for computing the mean monthly daily diffuse radiation:

$$D = 5.6K^{-0.55}(\sin\alpha_n)^{1.58} \tag{2}$$

where $\alpha_n = \sin^{-1}(\cos\phi\cos\delta + \sin\phi\sin\delta)$

In Malawi, work on the relationship between sunshine duration and global irradiation, for selected localities, has been done by several researchers including Zingano (1986) and Chikwembani (1993). Nevertheless, information is scarce on the distribution of diffuse radiation in the country. The objective of the present study was to examine selected models for estimating the mean monthly daily diffuse solar radiation.

2 METHODOLOGY

A set of global and diffuse solar radiation data (measured by Eppley pranometers connected to

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a Kipp & Zonen solar integrator over the period 1988 to 1991) was obtained from Chileka weather station (15°40′ S, 34°58′ E) in Blantyre. A pyranometer with a shadow ring was used to capture the diffuse (radiation?) data, which was corrected for the shadow-ring interception by default on a solar integrator (Kipp & Zonen, 1992). In addition, global radiation data (calculated from duration of sunshine over the period 1961 to 1990) was acquired from Makoka weather station (15°32′ S, 35°11′ E) which is not equipped with instruments for measuring the diffuse irradiance.

The daily extraterrestrial irradiation (H_{od}) was computed using a method reported by Jain Jain (1988):

$$H_{od} = 0.0036(24/\pi)I_{sc}\times E_o\{\cos\phi\cos\delta\sin\omega_s + (\omega_s\sin\phi\sin\delta)\} \quad (3)$$

where

$$E_o = 1.00011 + 0.034221\cos\Gamma + 0.00128\sin\Gamma + 0.000719\cos 2\Gamma + 0.000077\sin 2\Gamma,$$

$$\delta = 0.006918 - 0.03999\cos\Gamma + 0.07257\sin\Gamma - 0.006758\cos 2\Gamma + 0.000907\sin 2\Gamma - 0.002697\cos 3\Gamma + 0.00148\sin 3\Gamma,$$

$$\Gamma = 2\pi(N-1)/365,$$

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

Data was analysed using SPSS and Microsoft Excel computer programs. A linear regression was performed on the paired values of K and R to determine the coefficients of equation (1), (Birkes & Dodge, 1993).Further, the mean bias error (MBE) and root mean square error (RMSE) statistics were calculated to compare the performance of the models (Stone, 1993), (Young et al., 2001).

$$\text{MBE} = \left\{\sum(D_i - D_e)\right\}\Big/ n \quad (4)$$

$$\text{RMSE} = \left\{\sum(D_i - D_e)^2\Big/ n\right\}^{0.5} \quad (5)$$

3 RESULTS AND DISCUSSION

3.1 Present Correlation

A linear regression analysis shows that the Page (1979) model fits the local data well

(p-value = 0.00, $r^2 = 0.83$). The values of the regression constants a_0 and a_1 are shown in Table 1 and have 95% confidence intervals of (0.93, 1.22) and (−1.62, −1.06), respectively. The value of a[1] indicates that there is a negative correlation between the clearness index and diffuse fraction (Figure 1). This is consistent with findings of Page (1979) for temperate climates. The observed minor difference in the magnitudes of these coefficients is largely attributed to the variation in climatic conditions. With this level of confidence, the following correlation is extracted:

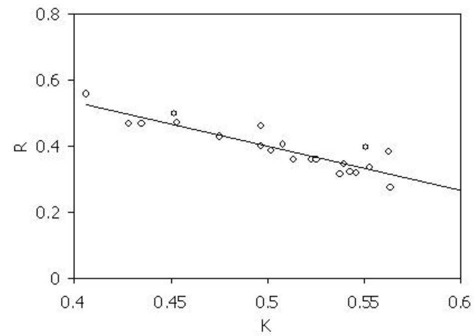

Figure 1: Variation of diffuse fraction (R) with clearness index (K) at Chileka

$$R = 1.07 - 1.34K \quad (6)$$

Equation (6) can be expressed in a direct form for estimating the intensity of diffuse radiation:

$$D = H(1.07 - 1.34K) \quad (7)$$

Table 1: Values of coefficients for the Page (1979) and present correlations.

Correlation	Coefficient a_0	Coefficient a_1
Page	1.00	-1.13
Present	1.07	-1.34

3.2 Comparison of Model Performance

Table 2 shows results of statistical comparison of the performance of the various correlations. The present correlation has the lowest magnitude of MBE while the Page (1979) correlation exhibits the highest degree of bias. Further, both the Page (1979) and Coppolino (1990) correlations have negative values of MBE, which indicates that they overestimate the mean monthly daily diffuse solar radiation. These observations are probably due to climatic influences. The Page (1979) and

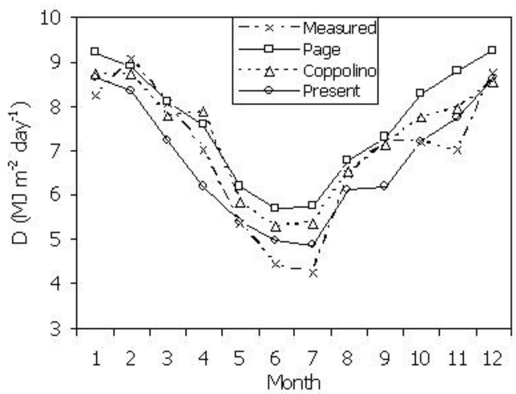

Figure 2: Comparison of measured and estimated levels of diffuse radiation at Chileka.

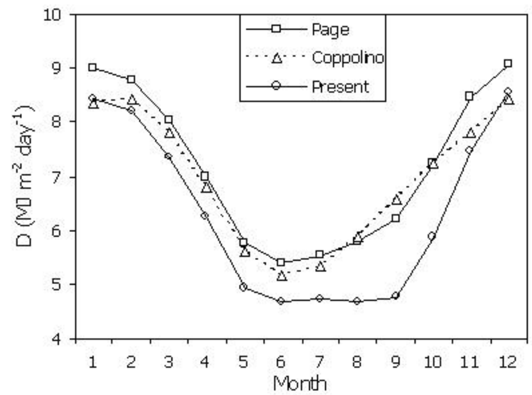

Figure 3: Comparison of estimated levels of diffuse radiation at Makoka.

Coppolino (1990) correlations were established using data from sites in the temperate regions with high air masses and degree of air pollution (due to industrialization) which generally augment the diffuse irradiance (Rapti, 2000), (Jacovides et al., 2000). In contrast, Chileka is located in a tropical region with a relatively low air mass and level of industrialization. The Coppolino (1990) correlation has the smallest value of RMSE while the present correlation has the largest value of RMSE. However, the variations in the values of RMSE are minor for all the correlations.

Table 2: Comparison of estimation errors.

Correlation	MBE	RMSE
Page (1979)	-0.611	0.8
Coppolino (1990)	-0.459	0.7
Present	+0.065	1.0

Figures 2 and 3 show a minimum of diffuse radiation between June and July and a maximum between December and January. This is attributed to the level of humidity which is generally low from May through October and high from December through February (Mitchell, 1993). The level of diffuse radiation increases with the concentration of atmospheric water vapour Rapti (2000). It is again observed that the Page (1979) and Coppolino (1990) correlations generally overestimate diffuse irradiance at both sites examined in this study, while the present correlation yields values that are below those deduced from the previous correlations.

NOMENCLATURE

D	mean monthly daily diffuse radiation on a horizontal surface (MJ m^{-2} day^{-1})
D_e	mean monthly diffuse radiation estimated by model (MJ m^{-2} day^{-1})
D_i	mean monthly diffuse radiation computed from measured values of daily diffuse radiation levels (MJ m^{-2} day^{-1})
E_o	eccentricity correction factor (dimensionless)
H	mean monthly daily global radiation on a horizontal surface (MJ m^{-2} day^{-1})
H_o	mean monthly daily extraterrestrial radiation on a horizontal plane (MJ m^{-2} day^{-1})
H_{od}	daily extraterrestrial radiation on a horizontal plane (MJ m^{-2} day^{-1})
I_{sc}	solar constant (1367 W m^{-2})
K	mean monthly sky clearness index (dimensionless)
MBE	mean bias error (MJ m^{-2} day^{-1})
n	number of observations
N	day of the year with $N = 1$ January 1.
R	mean monthly daily diffuse fraction (dimensionless)
RMSE	root mean square error (MJ m^{-2} day^{-1})
α_n	altitude of the sun at noon on the 15$^{\text{th}}$ day of the month (degrees)
δ	solar declination (rad)
ϕ	latitude of the location (degrees)
ω_s	sunset hour angle (rad)

4 CONCLUSION

The Page (1979) and Coppolino (1990) models for estimating the mean monthly daily diffuse irradiance have been studied. The Page model is simple and it can easily be used in feasibility studies for solar radiation applications. So, a linear correlation was formulated based on the Page model. The present correlation yields satisfactory statistical test results and provides good estimates of the diffuse component of solar radiation in Malawi.

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