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Original article

Estimation of monthly mean diffuse solar radiation over India: Performance of two variable models under different climatic zones

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ABSTRACT

In the present work, empirical models are proposed to estimate monthly-mean diffuse solar radiation on a horizontal surface under different climatic zones of India. Long-term meteorological data consisting of monthly average global and diffuse solar radiation together with sunshine duration for five major locations under prominent climatic zones was obtained from Indian Meteorological Department (IMD), Pune. Models with two inputs predictors (clearness index and sunshine ratio) under two categories i.e. diffuse fraction and diffusion coefficient were developed and compared (with each category consisting of eight models). Proposed models were also compared with well-established models from literature and were statistically analyzed to assess the performance. Global Performance Indicator (GPI) was used to organize models in order of best estimation capability within the two categories defined and among the overall group of sixteen models. Further, the developed models were also validated against subsets of measured data for five representative locations considered. Good agreement was found between estimated values from the developed models and the measured data. It was concluded that the developed models can conveniently be utilized to estimate diffuse solar radiation under varying climates within reasonable accuracy.

Introduction

Solar energy in India is available in abundant amounts across the year where the annual average global solar radiation value is of the order of 18.9 MJ/m^2-day [1–3]. Also, during the summer season, especially in the months of April and May this energy can be as high as 27 MJ/m^2-day in many regions [3–4].

Important data related to solar radiation availability is based on long-term precise measurement of incoming solar radiation and its components, especially diffuse radiation since it is severely affected by the local weather conditions, pollution levels and other suspended matter in the environment. Solar radiation is measured using pyranometers because these devices are static, have low maintenance and are easy to calibrate [5]. Only a few locations in India have the required measurement capabilities to assess quality solar radiation data [6]. The overall quality of available solar radiation is defined in terms of its components namely beam and diffuse solar radiation. Diffuse solar radiation or diffuse component provides important information for the development and utilization of solar based equipment and devices. Diffuse solar radiation measurements require expensive and sophisticated technological equipment.

Estimation of diffuse radiation through the use of empirical models based on mathematical functions thus plays an essential role in absence of required technological installations. Diffuse solar radiation is rationalized based on global solar radiation (known as 'diffuse fraction' or 'cloudiness index') or extraterrestrial solar radiation (known as 'diffusion coefficient' or 'diffuse transmittance') which are used to commonly express the diffuse component on a horizontal surface.

A number of approaches are available in literature to model horizontal diffuse solar radiation. Researchers have used various functional forms for the development of correlation equations at the location of interest. The most important predictors used for estimation of diffuse solar radiation are "clearness index" (ratio of global to extraterrestrial solar radiation) and "sunshine ratio" (ratio of sunshine hours to maximum possible sunshine duration). In view of this, most frequently used method for the development of diffuse solar radiation models is to correlate diffuse fraction or diffusion coefficient with clearness index and/or sunshine ratio. Many authors have suggested linear, nonlinear as well as piece-wise regression equations based on clearness index or sunshine ratio. This is because, under different sky-conditions, the mathematical representation can vary on the basis of available solar radiation and climatic conditions for an individual location selected. Authors like Iqbal [7], Liu & Jordan [8], Reindl et al. [9] and Angström [10] were among the primary researchers presenting their research on

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Nomenclature

$\overline{H}_d$	diffuse solar radiation on a horizontal surface (MJ/m^2-day)
$\overline{H}$	global solar radiation on a horizontal surface (MJ/m^2-day)
$\overline{H}_o$	extraterrestial radiation (MJ/m^2-day)
$\overline{H}_{ie}$,$\overline{H}_{im}$	i^{th} estimated and measured values of monthly mean daily solar radiation (MJ/m^2)
$\overline{H}_{m,av}$	mean of measured values of solar radiation (MJ/m^2)
H_{SC}	solar constant (W/m^2)
$\overline{k}_d$	diffuse fraction (or cloudiness index)
$\overline{k}_D$	diffusion coefficient
$\overline{k}_t$	clearness index
n	day of the year
R^2	coefficient of determination
$\overline{S}_o$	maximum possible sunshine duration (hours)
$\overline{S}$	sunshine duration (hours)

Greek letters

δ	angle of declination (degrees)
ϑ	sunshine ratio
ϕ	latitude (degrees)
ω_s	sunset hour angle (degrees)

Abbreviations

ECBC	Energy Conservation Building Code
GPI	Global Performance Indicator
IMD	Indian Meteorological Department
MAPE	Mean Absolute Percentage Error (%)
MBE	Mean Bias Error (MJ/m^2-day)
msl	Mean Sea Level (m)
RMSE	Root Mean Square Error (MJ/m^2-day)
t−stats	t-statistics

the development of diffuse solar radiation models. Empirical modeling for diffuse fraction has been most frequently proposed as regression functions of clearness index using linear, polynomial, logarithmic, exponential and power models [11–12].

Among some recent literature on single predictor models, Jamil & Akhtar [13] explored solar radiation measurements for Aligarh city situated in northern India and proposed linear regression model for diffuse fraction in terms of clearness index with a new set of regression coefficients. Jamil & Akhtar [14] developed sixteen models using the correlation between single input predictor i.e. clearness index under two different category as diffuse fraction and diffusion coefficient. They separated the whole data into training and validating data set. Training data set used for the development of the models while validating data set used to validate the models. Pandey & Katiyar [15] performed a detailed study on estimation of monthly diffuse radiation for four locations of India using measured data for five years and developed an 'All India correlation' between the diffuse fraction and sunshine ratio. They also proposed correlation using nonlinear and power relationship for the estimation of diffuse fraction at any location within India and compared the developed models with existing equations from literature. A comparison of hundred available monthly mean diffuse solar radiation models was performed by Jamil & Akhtar [16] by analyzing the diffuse fraction correlations on data observed over humid-subtropical climatic region of India. The selected models had variable (i.e. diffuse fraction) modelled in term of single predictor (clearness index). Statistical tools were employed to evaluate the suitability of estimation and ranking of the models. Khorasanizadeh et al. [17] proposed daily and monthly diffuse radiation models for the region of Kerman, Iran. They reported two categories of models viz., diffuse fraction and diffusion coefficient with clearness index as only input variable. Diffuse fraction linear model was concluded be the most accurate for estimation of daily values while diffusion coefficient linear model performed the best for estimation of monthly mean values. Six new models were developed by Jamil & Akhtar [18] correlating the diffuse fraction with clearness index using linear, quadratic, cubic, logarithmic, exponentials and power form equations. Based on the statistical analysis it was concluded that cubic model performed the best among the developed models. This was further verified by ranking of the models developed using Global Performance Indicator. Models were developed by El-Sebaii & Trabea [19], correlating diffuse fraction and diffusion coefficient with clearness index and sunshine hours for Egypt. Models under two categories viz., diffuse fraction and diffusion coefficient were reported with only one input predictor as clearness index. They concluded that diffuse fraction based linear function model was the most accurate for the estimation of daily values while for the best estimation of monthly mean values, diffusion coefficient linear function model outperformed the others. Empirical models to correlate diffuse fraction and diffusion coefficient with clearness index and sunshine duration was reported by Karkoti et al. [20]. The best fit model was concluded as cubic function of diffusion coefficient in terms of percent possible sunshine.

Some available literature based on correlation between diffuse fraction (or diffusion coefficient) with clearness index and sunshine ratio together are now described. Development of models by correlating diffuse fraction with two input predictors as sunshine ratio and clearness index together was originally proposed by Gopinathan [21]. Jamil & Siddiqui [22] analyzed diffuse solar radiation over India and proposed seven new models for diffuse fraction with clearness index and sunshine ratio together as predictors. The models were developed on training dataset and were tested on validation data set. The developed models were compared with the three available empirical models from the literature and statistical analysis was used to indicate the best model on training as well as validation dataset. Khalil & Shaffie [23] developed and performed comparative study of six models correlating diffuse fraction and diffusion coefficient using global solar radiation and sunshine duration for Cairo, Egypt. It was suggested that the analysis was significant for the regions with similar climates without meteorological information. Khorasanizadeh & Mohammadi [24] reviewed different functional forms of the models based on the number of input variables. The models were primarily categorized on the basis of correlation between (1) diffuse fraction or cloudiness index and (2) diffusion coefficient or diffuse transmittance index with number of different inputs. A total of 56 different models were reclassified into several main sub-categories and were presented in a sequential order of time. Gopinathan and Soler [25] reported diffuse fraction based models correlated with two predictors for 40 locations in the latitude range of 36°S to 60°N. Lewis [26] correlated diffuse fraction with clearness index and sunshine duration using the measured data of Memphis at Tennessee in USA. Gopinathan and Soler [27] suggested two input monthly average basis model using the data of 17 locations for France, Belgium, United Kingdom, Portugal, Italy and Greece. Trabea [28] also obtained two parameter monthly average diffuse solar radiation model for various location in Egypt. Mubiru & Banda [29] established two parameter monthly basis model for Kampala, Uganda. Jiang [30] developed the two parameter correlation with first and second order polynomial function monthly averaged models for 8 locations in China. In another article, Jiang [31] reported the development of daily basis two