An empirical model for estimating the monthly average daily global solar radiation from ground- and satellite-based meteorological data

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Abstract

This paper presents an empirical model for estimating the monthly average daily global solar radiation from ground- and satellite-based meteorological data of Thailand. The ground-based meteorological data are visibility, precipitable water, sunshine duration, and cloud fraction, while the satellite-based data are total column ozone. Five-year (2016–2020) ground- and satellite-based data from 14 meteorological stations were used to develop the model, and one-year data (2021) were employed to validate the model. The performance of the developed model was compared with that of seven existing models. It was found that the developed model performed better than the seven existing models. The root mean square difference relative to the mean measured values (RMSD) and the mean bias difference relative to the mean measured values (MBD) of the developed model were found to be 8.1% and 0.4%, respectively. The developed model gave a more accurate value of monthly average daily global solar radiation compared with the seven existing models.

Keywords:

Ground-Based Meteorological Data; Satellite-Based Meteorological Data; Solar Radiation Models; Solar Energy

1. Introduction

Solar radiation data are important for solar energy applications [1]. The monthly average daily global solar radiation ($\bar{H}$) data are usually used in design methods [1]. Global solar radiation can be obtained from a pyranometer at ground-based stations. However, the current number of stations is not sufficient for solar energy applications, particularly in developing countries; thus, the data need to be obtained via modeling approach. Several models have been proposed for estimating global solar radiation from meteorological data, which are more widely measured. Kimball [2] proposed the relationship between solar radiation and sunshine duration. Angstrom [3] proposed a model for estimating the daily average global solar radiation from sunshine duration. Instead, of using clear sky radiation to normalize the solar radiation in the radiation–sunshine model under all-sky conditions, Prescott [4] employed extraterrestrial radiation, through which the radiation can be more easily normalized. The author also proposed a model for estimating the global solar radiation from sunshine duration. The model included empirical coefficients that depend on the measurement area. Many other models with different model coefficients have been developed according to data from various countries [5]. Cloudiness has also been proposed to predict solar radiation [6]. Models relating solar radiation with cloud cover have been developed [6]. In agricultural communities, air temperature has been proposed to predict solar radiation [7]. Numerous solar radiation models have been proposed to estimate solar radiation using mainly ground-based meteorological data, including sunshine duration, cloudiness, air temperature, or a mixture of these variables as predictors [3-4, 8-14]. The drawback of these models is as follows: the predictor variables are not normalized, and they have different magnitudes, resulting in large errors, particularly when the models are applied for different locations from those with which the models were constructed. In addition, the *t*-statistic values [15] of each variable, which indicate the significance of the predictor variable [16], have not been reported. The main objective of the present study was to develop a model for estimating monthly average daily global radiation using data from both ground- and satellite-based meteorological variables with the report of t-statistic and the variables are normalized to avoid the problem of error caused by differences in magnitudes.

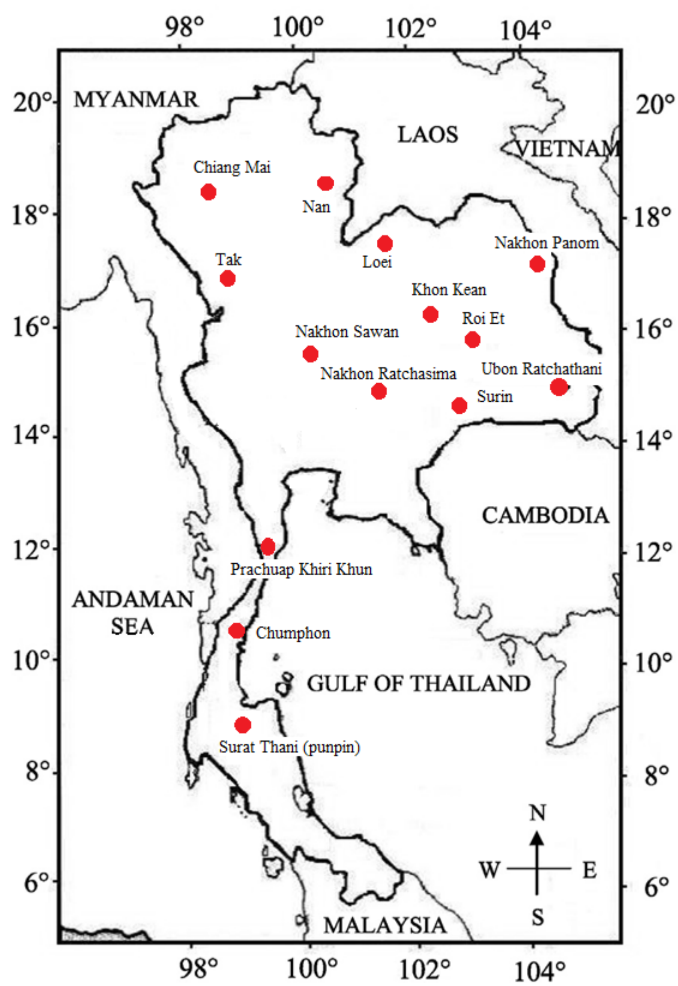

Fig. 1 The positions of the 14 stations where solar radiation (H), sunshine duration (S), relative humidity (Rh), ambient air temperature (T), cloud cover (C), and visibility (Vis) were measured and the data are used in this study.

2. Data

2.1. Ground-based data

The ground-based data includes global solar radiation (H), sunshine duration (S), relative humidity (Rh), ambient air temperature (T), cloud cover (C), and visibility (Vis). These parameters were measured at 14 meteorological stations in Thailand (Fig. 1). Rh, T, C, and Vis were usually measured every 3 h. These data were interpolated to obtain the hourly values. H, Rh, C, and Vis were simultaneously measured or observed from 14 Thai stations. The H-measuring equipment belonged to the Department of Alternative Energy Development and Efficiency, and the equipment for measuring S, Rh, T, C, and Vis belonged to the Thai Meteorological Department (TMD). All instruments were regularly calibrated and the measurements were conducted by well-trained officers of TMD. The data (January 2016–December 2020) from the 14 stations were collected for model development, and January–December 2021 data were employed to validate the model. Moreover, the performance of the developed model was compared with that of seven existing models. The positions of the stations are shown in Fig. 1.

2.2. Satellite-based data

As ozone affects shortwave radiation and ozone data are now available on the Internet, satellite-derived ozone data from OMI/ Aura were used in this study. The ozone data were downloaded from https://avdc.gsfc.nasa.gov/pub/data/satellite/Aura/OMI/V03/L2OVP/OMTO3/ for the positions of the 14 stations. The details of all the data used in this work are presented in Table 1.

Table 1. Details of data used in this work. H denotes the daily global solar radiation (Jm^{-2}), S denotes sunshine duration (h), Rh denotes relative humidity (-), T denotes ambient air temperature (°C), C denotes cloud cover (-),Vis denotes visibility (km), and O_3 denotes the total ozone column (cm). The data period for H, S, Rh, T, C, Vis, O_3 is from January 2016 to December 2021.

Stations	Location	
	Latitude (°N)	Longitude (°E)
Northern region		
1. Chiang Mai	18.78	98.98
2. Nan	18.72	100.75
3. Tak	16.80	98.90
Northeastern region		
4. Loei	17.40	101.00
5. Nakhon Panom	16.97	104.73
6. Khon Kean	16.45	102.78
7. Roi Et	16.07	103.00
8. Ubon Ratchathani	15.28	105.14
9. Nakhon Ratchasima	14.97	102.08
10. Surin	14.88	103.50
Central region		
11. Nakhon Sawan	15.67	100.12
12. Prachuap Kiri Khun	11.83	99.83
Southern region		
13. Chumphon	10.40	99.18
14. Surat Thani (punpin)	9.13	99.15

3. The developed model

The monthly average daily global solar radiation is affected by ozone, water vapor, aerosols, and clouds [16]. As water vapor is a function of relative humidity and temperature, precipitable water calculated from relative humidity and temperature using a model presented in Janjai et al. [17] was included in the model. Aerosols also affect the incident solar radiation, and aerosols could be qualified by visibility [16]. Consequently, visibility was included in the model. Sunshine duration was also included in the model as it is strongly related to global radiation [16]. Clouds affect directly solar radiation. Cloud information in terms of the cloud fraction was also included in the model. According to the above-mentioned information, a model for estimating the monthly average daily global solar radiation was proposed, as follows:

$$\frac{\bar{H}}{\bar{H}_0} = a_0 + a_1 \frac{\bar{O}_3}{\bar{O}_{3,max}} + a_2 \frac{\overline{Vis}}{\overline{Vis}_{max}} + a_3 \frac{\bar{w}}{\bar{w}_{max}} + a_4 \frac{\bar{S}}{\bar{S}_0} + a_5 \frac{\bar{C}}{\bar{C}_{max}} \quad (1)$$

where $\bar{H}$ = the monthly average daily global radiation (Jm^{-2});
$\bar{H}_0$ = the monthly average daily extraterrestrial radiation (Jm^{-2});
$\bar{O}_3$ = the monthly average daily ozone amount (DU);
$\bar{O}_{3,max}$ = the maximum monthly average daily ozone amount (285 DU);
$\overline{Vis}$ = the monthly average daily visibility (km);
$\overline{Vis}_{max}$ = the maximum monthly average daily visibility (12.26 km);
$\bar{w}$ = the monthly average daily precipitable water (cm);
$\bar{w}_{max}$ = the maximum monthly average daily precipitable water (6.05 cm);
$\bar{S}$ = the monthly average daily sunshine duration (h);
$\bar{S}_0$ = the monthly average daily daylength (h);
$\bar{C}$ = the monthly average daily cloud fraction (-);
$\bar{C}_{max}$ = the maximum monthly average daily cloud fraction (-);

a_0, a_1, a_2, a_3, a_4, and a_5 are empirical coefficients. $\bar{H}_0$ was obtained via the method described in Iqbal [16].

The model (equation 1) was fitted to the data from 14 stations, and the results are shown in Table 2.

Table 2 Values of empirical coefficients of the developed model.

coefficients	values	*t*-statistic	*p*-value
a_0	0.367939	8.62521	0.000000
a_1	−0.132825	−2.82328	0.004872
a_2	0.114606	6.25938	0.000000
a_3	0.047032	3.18933	0.001482
a_4	0.351690	20.86461	0.000000
a_5	−0.049349	−2.97883	0.002981

R^2 = 0.71 and N = 805 (R^2 is the coefficient of determination, and N is the total number of data points).

From Table 2, the absolute *t*-statistic values of all of the coefficients are greater than 2, indicating that all variables presented in the model are significant predictors of the monthly average daily global radiation [15].

The performance of the developed model was compared with those of seven existing models with the local coefficients (Table 3). These existing models were selected owing to their simplicity and popularity. The existing models were used to estimate the monthly average daily global radiation, and the outcomes were compared with that of the developed model for 2021. The comparison results are shown in Table 4.

Table 3 Existing models with the local coefficients.

Model	Mathematical forms of the other models	Input variables
Model 1 [9]	$\frac{\bar{H}}{\bar{H}_0} = 0.774972 - 0.33332\frac{\overline{Rh}_{mean}}{100}$	$\overline{Rh}_{mean}$ is the monthly average daily relative humidity of ambient air (%).
Model 2 [11]	$\frac{\bar{H}}{\bar{H}_0} = 0.663958 - 0.24014(\frac{\overline{Rh}_{mean}}{100})^2$	$\overline{Rh}_{mean}$ is the monthly average daily relative humidity of ambient air (%).
Model 3 [14]	$\frac{\bar{H}}{\bar{H}_0} = 0.7644877 - 0.00493\bar{T}_{mean}$	$\bar{T}_{mean}$ is the monthly average daily ambient air temperature (°C).
Model 4 [3-4]	$\frac{\bar{H}}{\bar{H}_0} = 0.321399 + 0.375072\frac{\bar{S}}{\bar{S}_0}$	$\bar{S}$ is the monthly average daily sunshine duration (h). $\bar{S}_0$ is the monthly average daily daylength (h).
Model 5 [10]	$\frac{\bar{H}}{\bar{H}_0} = 0.658057 - 0.25753\frac{\bar{C}_{mean}}{10}$	$\bar{C}$ is the monthly average daily cloud fraction (-). The sky is divided into 10 parts.
Model 6 [13]	$\frac{\bar{H}}{\bar{H}_0} = 1.719793 - 0.09136\bar{T}_{mean} + 0.001717\bar{T}_{mean}^2$	$\bar{T}_{mean}$ is the monthly average daily ambient air temperature (°C).
Model 7 [12]	$\frac{\bar{H}}{\bar{H}_0} = 0.965226 - 0.00598\bar{T}_{mean} - 0.3772\frac{\overline{Rh}_{mean}}{100}$	$\bar{T}_{mean}$ is the monthly average daily ambient air temperature (°C). $\overline{Rh}_{mean}$ is the monthly average daily relative humidity of ambient air (%).

From Table 4, model 4 having the sunshine duration as a predictor yields quite good mean bias difference (MBD) and root mean square difference (RMSD), possibly because sunshine duration is generally a good predictor of monthly average daily global radiation [16]. However, our developed model yields better MBD and RMSD for the combined data, as our model also considers sunshine duration as a predictor as well and for short wavelengths, our model also considers the ozone.

Table 4 Comparison of the performances of the developed model and existing models in terms of the mean bias difference relative to the mean measured value (MBD) and the root mean square difference relative to the mean measured value (RMSD).

Stations	Proposed model		Model 1		Model 2		Model 3		Model 4		Model 5		Model 6		Model 7	
	MBD (%)	RMSD (%)	MBD (%)	RMSD (%)	MBD (%)	RMSD (%)	MBD (%)	RMSD (%)	MBD (%)	RMSD (%)	MBD (%)	RMSD (%)	MBD (%)	RMSD (%)	MBD (%)	RMSD (%)
1. Chiang Mai	7.8	8.7	8.7	14.1	9.4	14.6	3.6	12.5	6.3	6.9	3.0	6.7	4.1	12.2	6.2	11.6
2. Nan	6.9	9.2	2.0	5.3	2.5	5.5	-0.4	4.6	3.7	6.4	10.5	13.0	-0.5	4.6	1.6	3.5
3. Tak	-2.5	5.4	9.2	18.5	9.6	18.7	3.1	18.0	0.5	5.2	8.2	13.5	4.4	17.9	6.6	15.8
4. Loei	-0.2	8.0	4.5	10.4	5.1	10.6	1.8	11.1	-1.7	7.7	8.4	9.3	1.8	10.8	3.5	8.5
5. Nakhon Panom	8.9	11.2	7.5	13.7	8.1	14.0	2.6	12.1	7.7	12.6	7.1	14.2	3.4	11.8	5.0	11.7
6. Khon Kean	-4.6	8.7	-1.7	9.0	-1.1	8.7	-5.9	12.4	-5.0	9.2	-6.5	10.5	-5.4	12.0	-3.4	10.0
7. Roi Et	5.3	8.3	-1.3	11.4	-0.7	11.2	-6.0	14.9	3.7	7.3	-3.7	9.8	-4.9	14.8	-3.6	10.1
8. Ubon Ratchathani	-3.7	7.8	-5.7	11.9	-5.2	11.4	-8.1	15.4	-3.7	7.9	-7.5	11.9	-7.7	14.9	-7.5	12.0
9. Nakhon Ratchasima	-3.1	6.6	1.8	8.7	2.3	8.5	-1.7	12.7	-4.5	7.4	-2.6	8.4	-0.6	11.7	-1.6	8.7
10. Surin	-6.5	10.7	-2.6	8.6	-2.1	8.3	-6.8	12.9	-5.0	10.6	-3.9	7.3	-6.2	12.7	-4.7	8.4
11. Nakhon Sawan	5.8	8.3	4.5	7.8	5.1	8.2	-2.8	9.9	5.5	7.7	1.6	8.0	0.4	7.3	0.0	7.9
12. Prachuap Kiri Khun	-2.6	5.9	-0.9	12.0	-0.3	11.9	-3.2	13.4	-2.9	5.8	-2.8	9.4	-2.8	13.3	-3.9	12.3
13. Chumphon	1.5	7.0	7.4	17.9	7.6	17.7	9.0	20.2	1.1	7.0	6.8	13.1	8.4	19.9	5.0	17.0
14. Surat Thani (punpin)	-1.3	6.5	1.7	15.5	1.8	15.1	3.9	18.3	-7.8	16.0	2.5	11.6	3.1	18.1	-0.3	15.5
Combined data	**0.4**	**8.1**	**2.3**	**12.4**	**2.7**	**12.4**	**-1.0**	**14.2**	**-0.4**	**8.9**	**1.0**	**10.6**	**-0.4**	**13.8**	**-0.1**	**11.6**

4. Conclusion

In this study, a model for calculating the monthly average daily global radiation was developed according to five-year ground- and satellite-based meteorological data (January 2016–December 2020) from 14 stations in Thailand. All variables in the model were normalized, and the *t*-statistic values were reported. A comparison between the developed model and existing models showed that the developed model was more accurate.

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