Diffuse-global correlation models at four locations in Thailand

Serm Janjai

Solar Energy Research Laboratory, Department of Physics, Faculty of Science,
Silpakorn University, Nakhon Pathom 73000, Thailand
Tel.: +66-34-270 761; Fax: +66-34-271 189
E-mail: serm@su.ac.th

Abstract

Diffuse-global correlation models at four solar monitoring stations in the tropical environment of Thailand have been investigated. These stations are located at Chiang Mai (18.78 °N, 98.98 °E) in the North of the country, Ubon Ratchathani (15.25 °N, 104.87 °E) in the Northeast, Nakhon Pathom (13.82 °N, 100.04 °E) in the Central region and Songkhla (7.20 °N, 100.60 °E) in the South. The models are based on a 12-year period of global and diffuse solar radiation data obtained from these stations. The models relate statistically the diffuse fraction of global radiation as a dependent variable to a clearness index, defined as the ratio of global radiation to extraterrestrial radiation for hourly, daily and monthly average time scales. The model performance was validated against independent data from these stations and satisfactory results were obtained. The models compared favorably with other available models when tested against these independent data.

Keywords: *Solar energy, solar radiation, diffuse-global correlation models, tropical environmen*t

1. Introduction

Global solar radiation incident on a horizontal surface is composed of two components, namely direct and diffuse components. The direct component is the radiation which travels approximately in a straight line from the sun through the earth's atmosphere to a point of interest at the earth's surface. The diffuse component is the solar radiation which is scattered by air molecules, aerosols, clouds and multiple reflections between the ground and the atmosphere. For a number of solar energy applications, especially those involving flat-plate solar collectors, it is necessary to know both the direct and diffuse components of the incident global radiation. However, most solar radiation monitoring stations measure only global radiation. For example, among 38 stations of a new network of the solar radiation monitoring stations of Thailand, only two stations measures diffuse radiation [1]. Therefore, diffuse and direct radiation have to be obtained by using model calculations.

In the pioneering work of Liu and Jordan [2], a one-parameter correlation between the diffuse to global ratio, which is usually called the diffuse fraction, and clearness index (global radiation/extraterrestrial radiation) has been proposed to estimate the diffuse radiation. Afterwards, a number of investigators have developed similar correlation models for hourly [3-13] daily [14-19] and monthly average daily [20-21] radiation using solar radiation data collected from various parts of the world. More recently, Torres et al. [22] have compared the performance of various models in estimating hourly diffuse solar irradiance in Pamplona, Spain and recommended suitable models for this location. From this literature survey, it is evident that the diffuse-global correlation models depend on the radiation climate of the data recording stations and averaging procedures [3-22].

At present, there are still limited studies on diffuse-global correlation models in the tropic [23-25]. Therefore, the objective of this study is to investigate diffuse-global correlation models for a tropical environment of Thailand.

2. Measurements and data

Due to the lack of global and diffuse solar radiation for solar energy research and applications, we have established four solar radiation monitoring stations in four main regions of Thailand. These stations are located at Chiang Mai (18.78 °N, 98.98 °E) in the North of the country, Ubon Ratchathani (15.25 °N, 104.87 °E) in the Northeast, Nakhon Pathom (13.82 °N, 100.04 °E) in the Central region and Songkhla (7.20 °N, 100.60 °E) in the South (Fig. 1). The stations are situated in a tropical environments characterized by high solar radiation and humidity year round. A 13-year period (1995-2007) of global and diffuse solar radiation data obtained from these stations was used in this study.

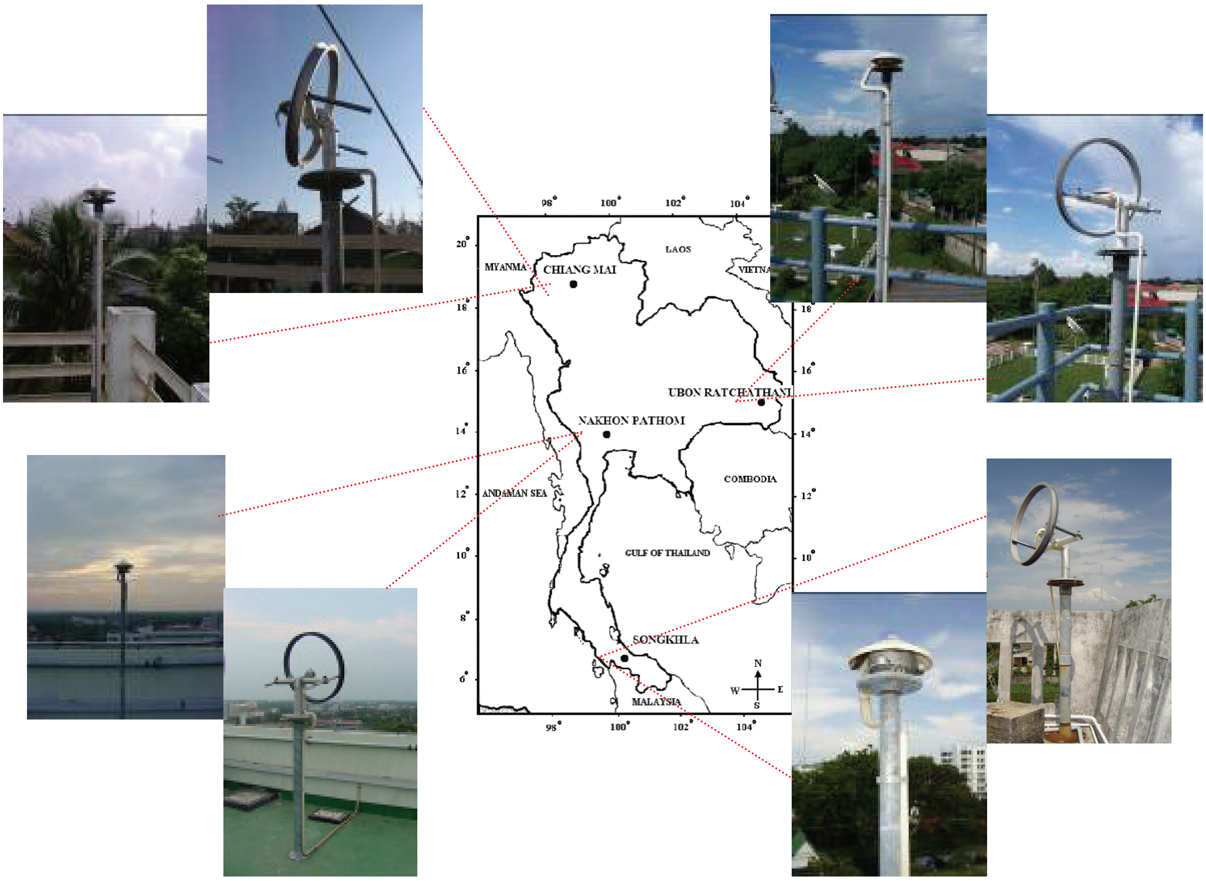

Fig. 1 Map of Thailand showing the locations of the solar radiation monitoring stations

Global radiation at Chiang Mai, Ubon Ratchathani and Songkhla was measured using Kipp&Zonen pyranometers (model CM21) whereas a pyranometer produced by the same company (model CM11) was employed for monitoring global radiation at Nakhon Pathom. Diffuse radiation at the four stations was measured by Kipp&Zonen pyranometers (model CM11) equipped with shade rings (model CM121) fabricated by the same company. For each station, voltage signals from the pyranometers were recorded using a Yokogawa (Model DC100) data logger. The signal was captured every second and averaged over a time period of 10 minutes. The averaged data were recorded in the memory of the data logger and downloaded at the end of every month. They were then sent to Solar Energy Research Laboratory, Silpakorn University by email. At the Laboratory, the voltage signals were converted to solar irradiance using the calibration constants of the pyranometers. The averaged 10-minute irradiance data were then integrated over a period of one hour and one day to obtain hourly and daily radiation, respectively. The pyranometers were calibrated employing a traveling pyranometer as a standard, with this instrument being calibrated at the Kipp&Zonen office in Holland. The shade rings for measuring diffuse radiation were adjusted every day and the glass domes of the pyranometers were regularly cleaned.

A 13-year period (1995-2007) of hourly diffuse and global radiation data from the four stations were manually checked for instrument or data processing errors. Data which violated physical laws were eliminated. These included negative global or diffuse radiation during daytime, diffuse irradiance exceeding global irradiance, and others. A table of correction factors supplied by Kipp&Zonen was also used to correct the effect of the shade ring on the diffuse radiation.

3. Development of the model

The solar radiation data from the four stations were separated into two groups. The first group (1995-2006) was used for formulating the diffuse-global correlation models whereas the second group (2007) was employed for model validation. The development of models for the case of hourly, daily and monthly average daily data are as follows.

3.1 Hourly solar radiation

To formulate the models for the case of hourly data, hourly diffuse fraction (k_d) and hourly clearness index (k_T) were calculated. The hourly diffuse fraction was defined as the ratio of hourly diffuse radiation (I_d) to hourly global radiation (I) and k_T is the ratio of hourly global radiation to hourly extraterrestrial radiation (I_0). I_0 was computed by using the formula reported in Iqbal [26]. Then the values of I_d / I were plotted against those of k_T. The results are shown in Fig. 2.

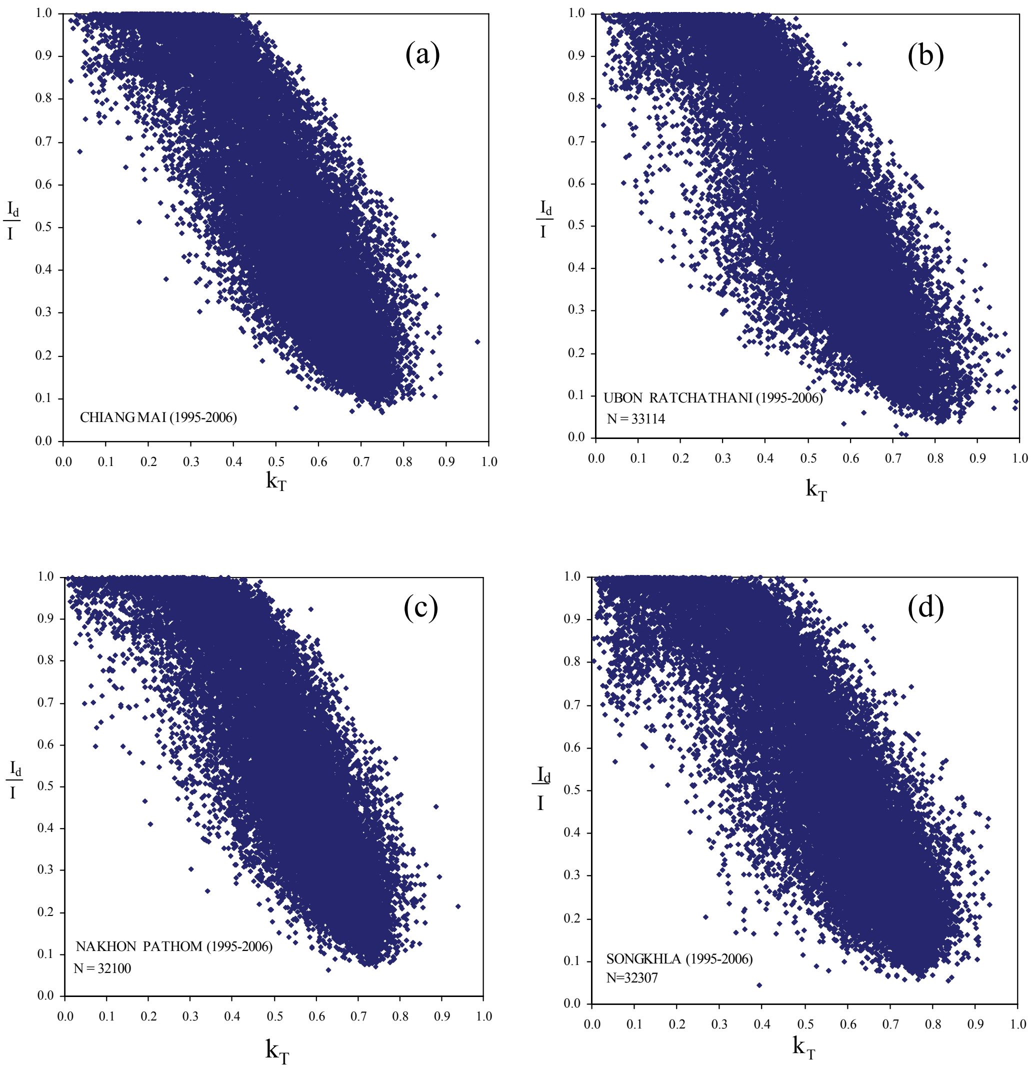

Fig. 2 Scattered plot of hourly diffuse fraction (I_d / I) against hourly clearness index (k_T) for a) Chiang Mai b) Ubon Ratchathani c) Nakhon Pathom and d) Songkhla. (N is total number of data.)

Figure 2 shows considerable scatter in all four stations. This is due to the fact that the main factor affecting I_d and I are clouds and cloud structure has a random nature [27]. Despite the scatter, the graphs for all stations exhibit a similar trend, with the diffuse fraction (I_d/I) decreasing with increasing of the clearness index (k_T). Diffuse radiation decreases with cloud cover eventually reaching cloudless conditions when it might amount to 20 to 25 percents of global radiation depending on aerosol conditions (Fig. 2). Compared to a cloudy environment, diffuse radiation is more conservative in cloudless skies, with greater values of k_T, since solar radiation scattering by air molecules and aerosols in clear skies is much lower than scattering by cloud droplets in cloudy skies. Songkhla (Fig. 2d) exhibits greater scatter than the other stations and this effect might be due to a different cloud structure in this marine tropical environment, with higher frequency of cumulonimbus clouds and higher sea salt particle aerosols characterized by high single scattering albedo [28].

The relation between I_d/I and k_T for each station can be best-fitted by the empirical models in Table 1 and the best-fitted graphs are shown in Fig 3.

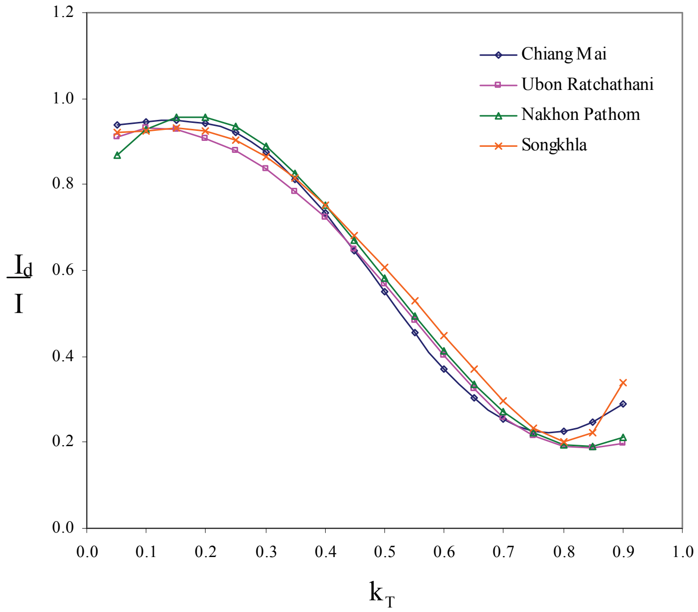

Fig. 3 Comparison of the best-fitted graphs of hourly diffuse fraction (I_d/I) against hourly clearness index (k_T)

Table 1 Models relating the diffuse fraction (I_d/I) and clearness index (k_T) at the hourly scale. R is correlation coefficient

Stations	Models	R^2
Chiang Mai	$I_d/I = -15.485 k_T^5+39.1626 k_T^4-30.356k_T^3+6.4927 k_T^2 -0.3707 k_T+0.9429$	0.76
Ubon Ratchathani	$I_d/I = -30.637 k_T^6+84.476 k_T^5-85.804 k_T^4+42.888 k_T^3 - 13.425k_T^2+1.841k_T +0.846$	0.71
Nakhon Pathom	$I_d/I = 5.3811 k_T^3-8.148 k_T^2+2.3552 k_T +0.7699$	0.73
Songkhla	$I_d/I = 49.900 k_T^6-129.643 k_T^5+133.679 k_T^4-66.222k_T^3 +13.501 k_T^2-1.046 k_T +0.949$	0.79

To examine their performance, the models were used to estimate diffuse irradiance for the year 2007, a data set that was not used to construct the above statistical models. The results are shown in Table 2.

The 2007 data set was also used to validate other models reported in the literature [3-13]. The results are also shown in Table 2.

Table 2 Comparison of the performance of the hourly models of this study with that of other model

Model	Chiang Mai		Ubon Ratchathani		Nakhon Pathom		Songkhla	
	RMSD (%)	MBD (%)	RMSD (%)	MBD (%)	RMSD (%)	MBD (%)	RMSD (%)	MBD (%)
Proposed models	27.4	-4.3	26.2	-6.1	29.6	0.04	19.8	-3.9
Orgill&Hollands [3]	30.3	6.1	25.9	2.5	34.4	2.4	19.6	-2.2
Erbs et al. [4]	29.1	5.5	25.4	1.2	33.3	2.5	20.5	-2.1
Hawlader [5]	32.2	1.7	32.4	1.0	36.2	0.4	21.7	-8.8
Reindl et al. [6]	29.7	5.3	25.9	2.0	33.5	2.1	19.6	-2.8
Chadrasekaran and Kumar	28.5	6.4	25.2	2.5	32.2	4.1	19.5	-1.3
[7]	30.0	10.0	25.8	6.1	33.2	7.2	19.3	0.1
Boland et al. [8]	29.7	5.3	25.7	1.6	33.6	2.0	19.6	-2.4
Miguel et al. [9]	32.4	-4.0	33.6	-5.1	37.2	-5.7	22.5	-9.4
Oliveira et al. [10]	30.3	-1.2	28.2	-3.8	32.8	-3.1	22.3	-8.6
Karatasou et al. [11]	34.4	-10.2	36.2	-11.3	38.4	-11.3	25.3	-14.6
Soares et al. [12]	29.5	0.3	30.5	-1.1	33.5	-0.9	21.0	-7.0
Jacovides et al. [13]								

For Chiang Mai, RMSD of the present model is the lowest whereas for Ubon Ratchathani the RMSD of the present models is comparable with that of Orgill and Hollands [3], Erbs et al. [4], Reindl et al. [6] Chandrasekaran and Kumar [7], Boland et al. [8] and Miguel et al. [9]. For the case of Nakhon Pathom, RMSD of the present models is the lowest. For Songkhla, RMSD of the present model is comparable with that of Orgill and Hollands [3], Reindl et al. [6], Chandrasekaran and Kumar [7], Boland et al. [8] and Miguel et al. [10]. The negative bias of the models for Chiang Mai, Ubon Ratchathani and Songkhla is likely due to the inter-annual variation of local aerosol loads which affect the diffuse fraction.

3.2 Daily solar radiation

Hourly data was integrated over a day to obtain daily radiation. The daily diffuse fraction, defined as a ratio of the daily diffuse radiation (H_d) to the daily global radiation (H) for each day, and the daily clearness index (K_T), defined as the ratio of daily global radiation to daily extraterrestrial radiation (H_0) were calculated. The values of K_T were then plotted against H_d/H (Fig. 4) and the best-fitted models for each stations are shown in Table 3 and Fig. 5 shows the comparison of the best-fitted graphs .

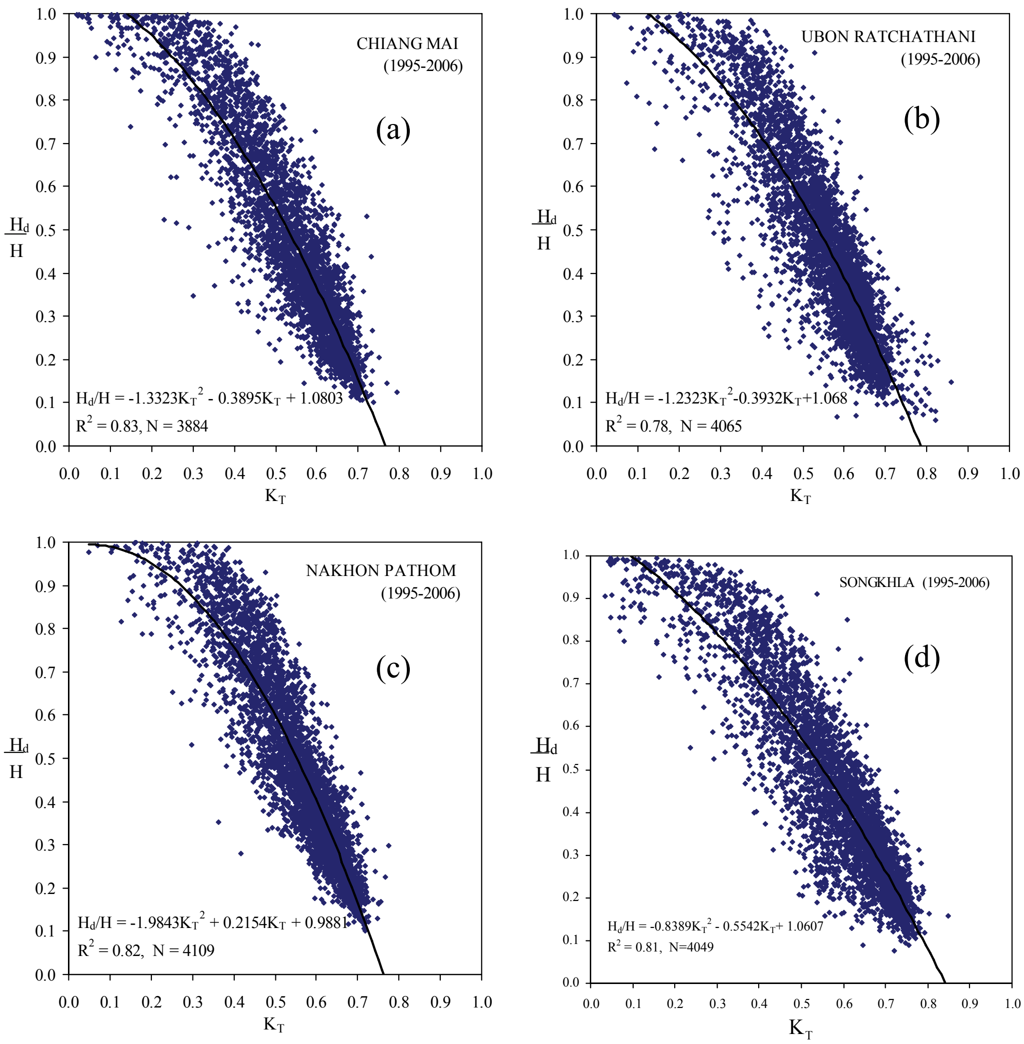

Fig. 4 Scattered plots of daily diffuse fraction (H_d / H) against daily clearness index (K_T) for a) Chiang Mai b) Ubon Ratchathani c) Nakhon Pathom and d) Songkhla

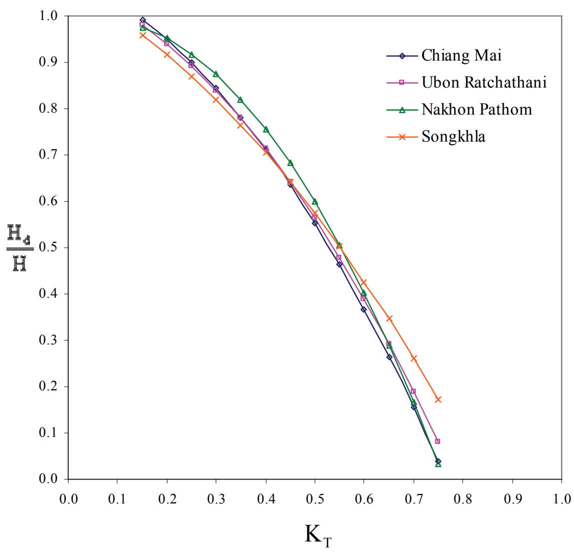

Fig. 5 Comparison of the best-fitted graphs of daily diffuse fraction (H_d / H) against daily clearness index (K_T)

Table 3 Models relating daily diffuse fraction (H_d / H) to daily clearness index

Stations	Models	R^2
Chiang Mai	$H_d/H = -1.3323K_T^2 - 0.3895K_T + 1.0803$	0.83
Ubon Ratchathani	$H_d/H = -1.2323K_T^2 - 0.3932K_T + 1.068$	0.78
Nakhon Pathom	$H_d/H = -1.9843K_T^2 + 0.2154K_T + 0.9881$	0.82
Songkhla	$H_d/H = -0.8389K_T^2 - 0.5542K_T + 1.0607$	0.81

From Fig. 4, it is observed that the scatter is less than the hourly data, resulting in higher values of the correlation coefficient. This is because temporal averaging removes some of the cloud structure variability. As in the hourly data, model performance was compared with that of the other models [2,10,14-19] by using an independent data set for the year 2007 at the four stations. Results are shown in Table 4.

Table 4 Comparison of the performance of the daily models of this study with that of the other models

Model	Chiang Mai		Ubon Ratchathani		Nakhon Pathom		Songkhla	
	RMSD (%)	MBD (%)	RMSD (%)	MBD (%)	RMSD (%)	MBD (%)	RMSD (%)	MBD (%)
Proposed models	17.4	-2.1	17.6	-4.3	19.5	4.9	16.8	-2.3
Liu and Jordan [2]	23.7	-11.0	24.9	-15.1	23.4	-9.8	26.4	-19.1
Collares-Pereira and Rabl [14]	20.4	8.6	17.4	3.3	21.7	9.0	16.9	-0.5
De Jong [15]	25.5	13.9	22.4	9.9	26.9	15.5	18.5	5.9
Newland [16]	18.4	2.8	17.1	-2.7	19.5	3.0	18.8	-8.0
Barbatunde and Aro [17]	27.5	-10.9	27.4	-13.4	26.7	-9.2	26.8	-15.6
Jacovides et al. [18]	18.3	3.3	16.9	-2.4	19.5	3.3	19.2	-8.3
Oliveira et al. [10]	29.9	-23.0	34.7	-29.1	31.9	-23.4	39.4	-33.7
Rensheng [19]	18.7	-1.6	18.9	-6.7	19.7	-0.9	20.5	-11.9

For Chiang Mai, the RMSD of the present model is the lowest. In the case of Ubon Ratchathani, the performance of our models is similar to those of Collares-Pereira and Rabl [14], Newland [16] and Jacovides et al. [18]. For Nakhon Pathom and Songkhla, RMSDs of our proposed models are among the lowest values.

3.3 Monthly average daily radiation

All daily data were averaged over a month to obtain a monthly average daily diffuse fraction $(\overline{H}_d / \overline{H})$, and monthly average daily clearness index, $\overline{K}_T$ ($\overline{K}_T = \overline{H} / \overline{H}_0$). $\overline{H}_0$ is monthly average daily extraterrestrial radiation. Finally the values of $\overline{H}_d / \overline{H}$ were plotted against $\overline{K}_T$ for all months (Fig. 6) and the best correlation equation between $\overline{H}_d / \overline{H}$ and $\overline{K}_T$ are presented in Table 5. The comparison of the best-fitted graphs is shown in Fig. 7

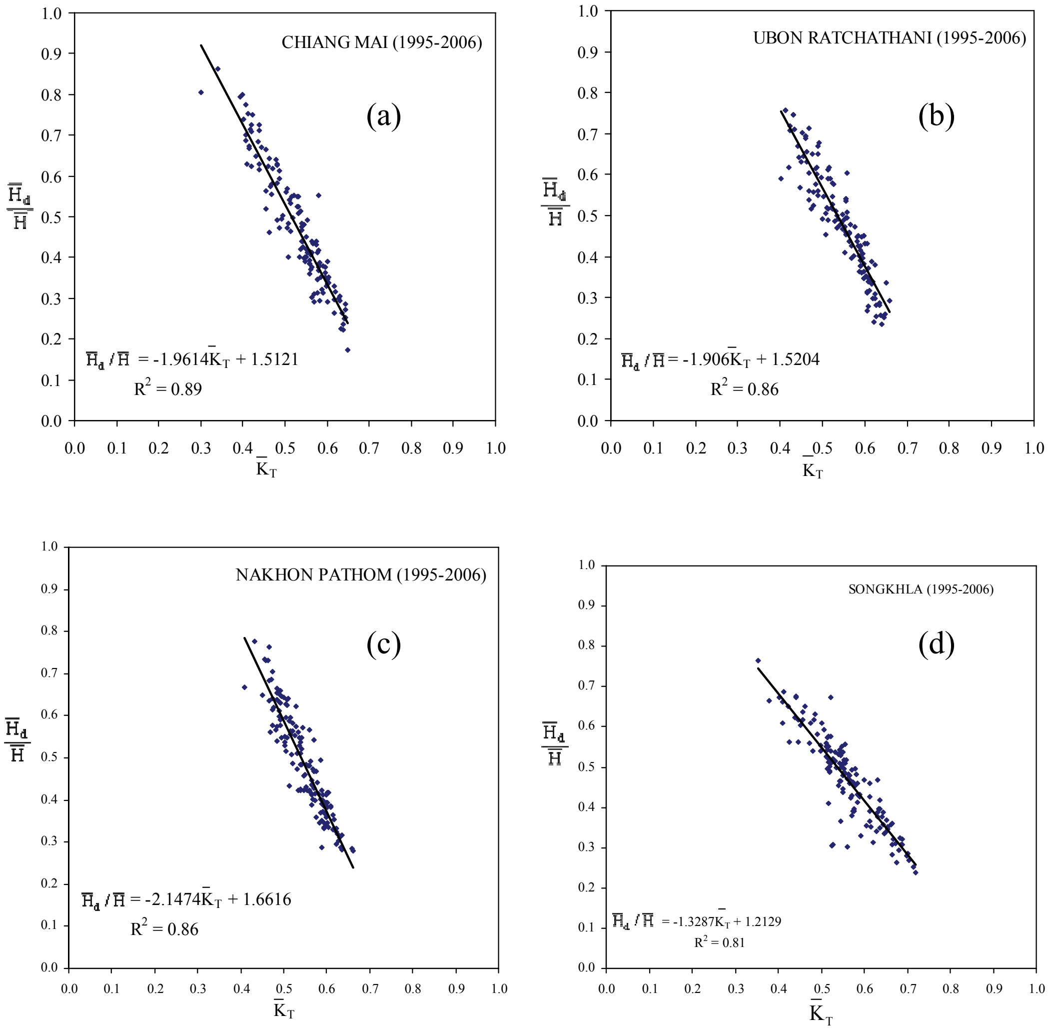

Fig. 6 Correlation between monthly average diffuse fraction $(\overline{H}_d/\overline{H})$ and monthly average daily clearness index ($\overline{K}_T$) for a) Chiang Mai b) Ubon Ratchathani c) Nakhon Pathom and d) Songkhla

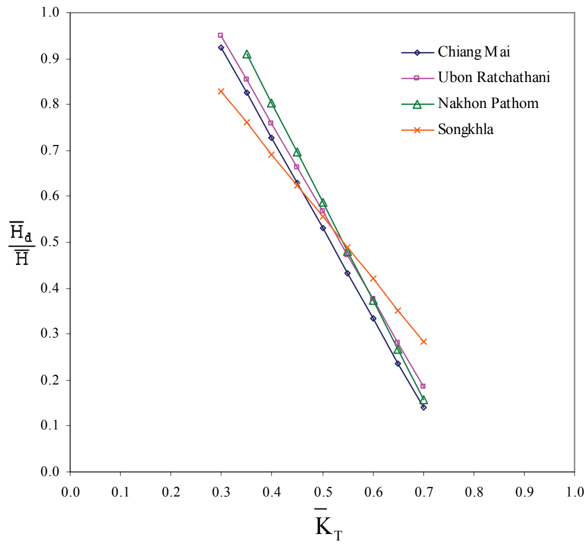

Fig. 7 Comparison of the best-fitted graphs of monthly average daily diffuse fraction ($\overline{H}_d/\overline{H}$) against monthly average daily clearness index ($\overline{K}_T$)

Table 5 Diffuse fraction models for the case of monthly average daily radiation

Stations	Models	R^2
Chiang Mai	$\overline{H}_d / \overline{H} = -1.9614\,\overline{K}_T + 1.5121$	0.89
Ubon Ratchathani	$\overline{H}_d / \overline{H} = -1.906\,\overline{K}_T + 1.5204$	0.86
Nakhon Pathom	$\overline{H}_d / \overline{H} = -2.1474\,\overline{K}_T + 1.6616$	0.86
Songkhla	$\overline{H}_d / \overline{H} = -1.3287592\,\overline{K}_T + 1.2129$	0.81

It is observed that $\overline{H}_d / \overline{H}$ correlates well with $\overline{K}_T$, with the values of R^2 ranging from 0.82 to 0.89. This is due to the averaging process which helps reduce the scattering of the data points. To investigate their performance, the models were employed to compute monthly average daily diffuse radiation for the year 2007. The results are shown in Table 6. The performance of the developed model was also compared with that of other models in literatures and the results were also shown in the same table.

Our models predict best the monthly average daily diffuse radiation with RMSD values in the range of 5.4% and 10.6%. These values are lower than those of other models.

Table 6 Comparison of the performance of the models for calculated monthly average daily diffuse radiation developed in these studies and that of the other models

Model	Chiang Mai		Ubon Ratchathani		Nakhon Pathom		Songkhla	
	RMSD (%)	MBD (%)	RMSD (%)	MBD (%)	RMSD (%)	MBD (%)	RMSD (%)	MBD (%)
Proposed models	9.1	1.8	5.4	3.2	10.6	9.9	9.8	-3.5
Liu and Jordan [2]	30.6	-24.8	30.6	-27.1	25.1	-22.1	33.2	-32.5
Page [20]	19.8	-13.5	20.0	-17.1	17.5	-10.4	26.4	-25.0
Erbs et al. [4]	21.3	-13.6	20.7	-16.4	18.4	-10.5	23.5	-22.6
Newland [16]	18.8	-12.3	18.9	-16.0	16.4	-9.2	25.6	-24.1
Oliveira et al. [10]	37.3	-35.8	42.7	-42.2	38.7	-33.4	50.1	-46.3
Paliatsos et al. [21]	14.9	-9.0	15.7	-14.0	12.7	-5.8	27.4	-24.5

4. Discussion

The task of estimating diffuse fraction of global radiation is made difficult by the complexity of the cloud field and the lack of diffuse radiation measurement stations. In many cases, a modeling approach is the most practical way of solving the problem, usually involving a statistical relationship between a clearness index and the diffuse fraction. The implicit assumption is that measurements of global radiation (and therefore the clearness index), is more easily accessible than diffuse radiation which is more difficult to monitor. However, the method still relies on the availability of stations that monitor both global and diffuse radiation. In this study, we have used four stations to develop four statistical relationships in different regions of the country. As discussed, these relationships are tuned to local conditions in the tropical environment and perform better than most models developed elsewhere under different radiation climates.

The issue still remains as to where the statistical relationship should be used, and in which region of the country. Examining the plots of the diffuse fraction vs clearness index (Fig. 2, 4 and 6) and the best-fitted graphs (Fig. 3, 5 and 7), certain relevant features appear. As the temporal averaging increases, the graphs of diffuse fraction vs clearness index become more linear and there are less scatter in the data, as cloud properties are spatially and temporally averaged. From Fig. 3, 5 and 7, it is observed that the best-fitted graphs of diffuse fraction vs clearness index of the three inland stations (Chiang Mai, Ubon Ratchathani and Nakhon Pathom) exhibit similar trends whereas the graphs of Songkhla show different pattern. This implies that for inland stations, a model of one station can be approximately used for other inland locations. However, due to the distinct characteristics of clouds and aerosols in the South, the diffuse fraction of this region has to be treated separately.

Although, the three inland has different levels of urbanization, the graphs still show similar trends. This implies that the models are not sensitive to the levels of urbanization. Consequently, these models are likely to be valid for both urban and rural environments. The models for Songkhla are expected to be valid for all maritime environment of the South.

In terms of the uncertainty of the models, the values of RMSD obtained from the model validation can be used to indicate the levels of the uncertainty. From Table 2, 4 and 6, the uncertainty of the models for the case of hourly data, daily data and monthly average daily data is in the ranges of 19.8-29.6%, 16.8-19.5% and 5.4 -10.6%.

As the data used for developing the models include a wide range of visibility, the proposed models are expected to be valid for all conditions of the visibility.

5. Conclusion

Based on a 12-year period data of global and diffuse solar radiation measured at four stations, located in a tropical environment of Thailand, diffuse-global correlation models have been formulated. The models statistically relate the diffuse fraction to the clearness index. The diffuse fraction of global irradiance is estimated for hourly, daily and monthly time scales. The model at each station compared favorably with other published models.

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