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Technical note

Modeling the hourly solar diffuse fraction in Taiwan

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ABSTRACT

Using the data for global and diffuse radiation in Tainan, Taiwan, for the years of 2011 and 2012, respectively, four correlation models with five predictors: the hourly clearness index (k_t), solar altitude, apparent solar time, daily clearness index and a measure of persistence of global radiation level, are constructed to relate the hourly diffuse fraction on a horizontal surface (d) to the clearness index. Two models use a single logistic equation for all k_t values, Eqs. (6) and (7), and the other two models use a set of piece-wise linear equations for four k_t intervals, Eqs. (8) and (9). The proposed models are compared respectively with the fourteen models available in the literature, in terms of the four statistical indicators: the mean bias error, the root-mean-square error, the *t*-statistic and the Bayesian Information Criterion, using the out-of-sample dataset for Tainan, Taiwan. It is concluded from the analysis that the proposed piece-wise linear models perform well in predicting the diffuse fraction, while the performances of the proposed logistic models are more case-dependent. Among those fourteen models considered in this study, the models developed by Erbs et al., Chandrasekaran and Kumar, and Boland et al. have competitive performances as the proposed piece-wise linear models do, when applying to the prediction of diffuse fraction in Tainan, Taiwan.

1. Introduction

Global radiation (I_{global}) consists of two parts: diffuse radiation ($I_{diffuse}$) and beam radiation (I_{beam}). Information about hourly diffuse fraction (d), defined in Eq. (1), is prerequisite to evaluate the performances of concentrating solar thermal systems. Since the measurements of diffuse or beam radiation are not frequently possible on a site of interest, it is necessary to find a model of diffuse fraction correlating the diffuse radiation to the global radiation which is usually available in the reports from the meteorological stations.

$$d = \frac{I_{diffuse}}{I_{global}} \tag{1}$$

An early model developed by Liu and Jordan [1] estimates d in terms of the hourly sky clearness index (k_t), which is an indicator to measure how clear the skies are, given by

$$k_t = \frac{I_{global}}{H_o} \tag{2}$$

where H_o is the hourly extraterrestrial radiation and can be theoretically determined by specifying the site latitude, the day of each year and the hour of each day [2]. The idea of such early model is rather simple: when k_t is large (clear sky), diffuse fraction is small due to less obstruction by small droplets and particulates suspended in the atmosphere; when k_t is small (cloudy sky), diffuse fraction is large because of the greater scattering frequency. Following the same idea, quite a few other models in terms of the single predictor k_t [3–12] were developed later, each of which successfully fit the data of diffuse fraction within a specified region, to varying degrees.

Studies that include multiple predictors in modeling to achieve a better data fit were also conducted. For example, Reindl et al. [13] suggested that the solar altitude (α), ambient temperature (T_a) and relative humidity (RH) are the other three effective ones, by performing a statistical analysis of twenty-eight possible predictors, using the data from cities worldwide.

Recently, Boland and his coworkers [14,15] demonstrated that the performance of the time-dependent model was better than the other and corroborated the significance of time (apparent solar

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time) as an extra model predictor. On the basis of these investigations, they recently proposed the Boland–Ridley–Lauret model (abbreviated as the BRL model hereafter) [16] using a total of five predictors: k_t, α, the apparent solar time (t), the daily clearness index (K_T) and a measure of persistence of global radiation level (ψ). The last two predictors are defined as follows.

$$K_T = \frac{\sum_{i=1}^{24} I_{\text{global}}}{\sum_{i=1}^{24} H_o} \tag{3}$$

$$\psi = \begin{cases} \frac{k_{t-1}+k_{t+1}}{2} & \text{for sunrise} < t < \text{sunset} \\ k_{t+1} & \text{for } t = \text{sunrise} \\ k_{t-1} & \text{for } t = \text{sunset} \end{cases} \tag{4}$$

Despite the abundance of models, such as those summarized in Tables 1 and 2, there is still a need for developing correlation models for the Taiwan area. According to the comparative studies of model performance made by Jacovides et al. [11], Torres et al. [17] and Dervishi and Mahdavi [18], most of the existing correlation models are not applicable to all geographical regions, without modification. Therefore, the developments of applicable but accurate correlation models for a specific region, which account for the geographical and climatic conditions, are still preferable.

This study correlates four models with two different mathematical formats: logistic and piecewise linear equations, using the two available yearly sets of data in Tainan, Taiwan. The logistic models, which are based on the recent study of Ridley et al. [16], use a single logistic equation for all values of k_t. In contrast, the other relatively simple models use a set of piece-wise linear equations for different intervals of k_t that use the same group of predictors as the logistic models. The models listed in Table 1 are also tested using the available database in Taiwan, for the purpose of comparison with the proposed models developed in this study.

2. Experimental set-up and database

Because of the lack of diffuse radiation data in daily reports from all meteorological stations of the Taiwan Central Weather Bureau, this modeling work uses the in situ data for global and diffuse radiation, measured at the Kuei-Jen campus of the National Cheng Kung University, Tainan, Taiwan (23°N 120°E), from 1 January 2011 to 31 December 2012.

Two sets of devices from Eppley Laboratory, Inc., each of which included a pyranometer (Model PSP) without and with a shadow band stand (Model SBS), were used to measure global and diffuse radiation, as shown in Fig. 1(a) and (b), respectively. The sampling rate was of 1 Hz. The method of data checking followed partially the ideas of Reindl et al. [13], to identify the missing data and data which violated physical limits. The missing data for individual seconds mostly occurred while transmitting were filled using a linear interpolation of the neighboring data in the time sequence. After all of the missing data had been filled, the data for individual seconds were converted into an hourly value by integration with respect to time.

Table 1
Summary of the models from the literature.

	Constraints	Diffuse fraction (d)
Orgill and Hollands, 1977 [3]	$k_t < 0.35$ $0.35 \le k_t \le 0.75$ $k_t > 0.75$	$1.0 - 0.249k_t$ $1.557 - 1.84k_t$ 0.177
Erbs et al., 1982 [4]	$k_t \le 0.22$ $0.22 < k_t \le 0.80$ $k_t > 0.80$	$1.0 - 0.09k_t$ $0.9511 - 0.1604k_t + 4.388k_t^2 - 16.638k_t^3 + 2.336k_t^4$ 0.165
Bugler, 1977 [5]	$0 < k_t \le 0.4$ $0.4 < k_t \le 1.0$	0.94 $(1.29 - 1.19k_t)/(1.00 - 0.334k_t)$
Hawlader, 1984 [6]	$k_t \le 0.225$ $0.225 < k_t < 0.775$ $k_t \ge 0.775$	0.915 $1.135 - 0.9422k_t - 0.3878k_t^2$ 0.215
Miguel et al., 2001 [7]	$k_t \le 0.21$ $0.21 < k_t \le 0.76$ $k_t > 0.76$	$0.995 - 0.081k_t$ $0.724 + 2.738k_t - 8.32k_t^2 + 4.967k_t^3$ 0.18
Karatasou et al., 2003 [8]	$0 < k_t \le 0.78$ $k_t > 0.78$	$0.9995 - 0.05k_t - 2.4156k_t^2 + 1.4926k_t^3$ 0.20
Chandrasekaran and Kumar, 1994 [9]	$k_t \le 0.24$ $0.24 < k_t \le 0.80$ $k_t > 0.80$	$1.0086 - 0.178k_t$ $0.9686 + 0.1325k_t + 1.4183k_t^2 - 10.1862k_t^3 + 8.3733k_t^4$ 0.197
Soares et al., 2004 [10]	$k_t \le 0.17$ $0.17 < k_t \le 0.75$ $k_t > 0.75$	1.0 $0.90 + 1.1k_t - 4.5k_t^2 + 0.01k_t^3 + 3.14k_t^4$ 0.17
Jacovides et al., 2006 [11]	$k_t \le 0.1$ $0.1 < k_t \le 0.8$ $k_t > 0.8$	0.987 $0.94 + 0.937k_t - 5.01k_t^2 + 3.32k_t^3$ 0.177
Zhou et al., 2004 [12]	$k_t < 0.20$ $0.20 \le k_t < 0.75$ $k_t > 0.75$	0.987 $1.292 - 1.447k_t$ 0.209
Reindl et al., 1990 [13]	$0 \le k_t \le 0.3$ $0.3 < k_t < 0.78$ $k_t \ge 0.78$	$1.000 - 0.232k_t + 0.0239\sin(\alpha) - 0.000682T_a + 0.0195\text{RH}$ $1.329 - 1.716k_t + 0.267\sin(\alpha) - 0.00357T_a + 0.106\text{RH}$ $0.426k_t - 0.256\sin(\alpha) + 0.00349T_a + 0.0734\text{RH}$
Reindl et al., 1990 [13]	$0 \le k_t \le 0.3$ $0.3 < k_t < 0.78$ $k_t \ge 0.78$	$1.020 - 0.254k_t + 0.0123\sin(\alpha)$ $1.400 - 1.749k_t + 0.177\sin(\alpha)$ $0.486k_t - 0.182\sin(\alpha)$
Boland et al., 2001 [14]	None	$-0.039 + 1.039/[1 + \exp(-8.769 + 7.325k_t + 0.377t)]$
Boland et al., 2008 [15]	None	$1/[1 + \exp(8.60k_t - 5.00)]$
Ridley et al. (BRL model), 2010 [16]	None	$1/[1 + \exp(-5.38 + 6.63k_t - 0.007\alpha + 0.006t + 1.75K_T + 1.31\psi)]$