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Modeling the luminous efficacy of direct and diffuse solar radiation using information on cloud, aerosol and water vapor in the tropics

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ABSTRACT

This paper presents luminous efficacy models for direct and diffuse solar irradiance using information on cloud, aerosol and water vapor in the tropics. The model is based on five years (2007–2011) of diffuse illuminance and irradiance measurements and two years of direct illuminance and irradiance measurements, April 2010–March 2012. Data are taken at four solar radiation monitoring stations in Thailand, specifically Chiang Mai (18.78 °N, 98.98 °E) in the Northern region, Ubon Ratchathani (15.25 °N, 104.87 °E) in the Northeastern region, Nakhon Pathom (13.82 °N, 100.04 °E) in the Central region and Songkhla (7.20 °N, 100.60 °E) in the Southern region. The models express luminous efficacy as functions of the aerosol optical depth and precipitable water, obtained from the AERONET network, and a cloud index for hourly time scales derived from the MTSAT-1R satellite. The model performance is good when validated against independent data from these stations. Root mean square differences (RMSD) of 9.7% and 6.8% for direct normal efficacy and diffuse efficacy, respectively are obtained. The models compared favorably with most existing models when tested against these independent data.

1. Introduction

Efficient use of daylight illumination can bring substantial savings in lighting costs [1]. Recognizing this importance, a number of countries are actively engaged in constructing systems which enhance daylight illumination in buildings, and eventually leading to the development of daylight-integrated buildings [2–10]. Such designs require reliable data on daylight illuminance, although the number of daylight monitoring stations where illuminance is routinely measured is sparse, especially in developing countries. As daylight illuminance is part of the solar spectrum, it is possible to establish a relation between solar illuminance and broadband solar irradiance. This relationship forms the basis of the term “efficacy”, and can be used to estimate illuminance from the more widely acquired broadband irradiance.

The efficacy K is commonly defined as a ratio of illuminance to irradiance. In general terms it may be written as:

$$K_i = 683\frac{\int_{380\text{ nm}}^{770\text{ nm}} I_{i\lambda}V(\lambda)d\lambda}{\int_{300\text{ nm}}^{3000\text{ nm}} I_{i\lambda}d\lambda} \tag{1}$$

where $I_{i\lambda}$ represents either direct, diffuse or global solar spectral irradiance, and $V(\lambda)$ is the photopic response as a function of wavelength λ. Thus the required illuminance variable is readily obtained as the product of the measured solar irradiance by the corresponding luminous efficacy. As visible and broadband radiation is absorbed and scattered by atmospheric constituents in different proportions, luminous efficacy usually varies with atmospheric parameters such as solar elevation and atmospheric composition including water vapor, aerosols and clouds. In its simplest form, the luminous efficacy has been taken as constants [11,12], but the majority of studies in the past few decades have developed models based on various environmental factors [13–26].

Results presented to date indicate the parameterizations to be strongly dependent on the required variable. Cloudless sky efficacy is dominated by solar elevation α and there have been a number of empirical relationships relating solar elevation to luminous efficacy

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for direct radiation. These usually take the form of polynomial functions of α [14,18,25], or more sophisticated relationships that use exponential functions [26]. Cloudy conditions must bring in some indices of atmospheric opacity to the calculation of direct, diffuse and global luminous efficacy. They involve several indices such as the ratio of the measured global or diffuse irradiance to the extra-terrestrial irradiance [16,17], a ratio of measured diffuse irradiance to measured global irradiance [18] or cloud cover determined from satellites [24].

The above relationships are all empirical and strongly linked to the local measurement environment. Therefore, any assessment of the model performance in other locations must take this into account. Comparisons performed by Souza et al. and Souza and Robledo [23,27] showed strikingly improved performance when coefficients from various models available in the literature were adjusted for local conditions. This task enabled an objective comparison to be made of various model performances.

Assessing model performances for cloudy skies require some careful considerations. Low-level clouds which contribute to the greatest depletion of solar radiation reaching the earth's surface are notoriously variable in their structure and composition as they are fractals in nature [28].

In this work, we propose efficacy models which include the effect of various atmospheric parameters. Cloud opacity is treated using a satellite-derived cloud index, therefore providing comprehensive and regular cloud information throughout the country. The models are developed for this tropical environment, in many ways different from the mid-latitudes. Cloud structures are expected to be different, with towering convective clouds reaching their greatest height during the wet season. Other environmental factors not taken into account in previous models may also affect the accuracy of the results. The tropical environment of Thailand experiences high levels of relative humidity especially during the wet season. Water vapor absorbs differently the visible and near infrared (NIR) regions of the solar spectrum, so that precipitable water vapor might be a useful term to be included in the empirical models [15,29].

Clearness and brightness indices have been developed as means of identifying cloud episodes [15] but aerosol depletion has not been treated explicitly although it is an important depletion agent in the Thailand environment. Aerosols tend to have a lower depletion in the NIR portion of the spectrum, away from the photopic region (380–770 nm) which implies that the luminous efficacy might be sensitive to aerosol optical depth.

Therefore, the main objective of this work is to model diffuse and direct luminous efficacy based on information on precipitable water vapor, surface-derived aerosol optical depth and satellite-derived cloud index. The modeling is based on illuminance and irradiance measurements taken at four solar radiation monitoring stations in Thailand.

2. Measurements and data

2.1. Ground-based measurements

Radiation monitoring stations have been deployed in each of the main geographical regions of Thailand (Fig. 1). Chiang Mai (18.78 °N, 98.98 °E) is the northernmost station which is situated in the mountainous north and characterized by cool winter. The station located in Ubon Ratchathani (15.25 °N, 104.87 °E) represents the dry northeastern highland, followed by Nakhon Pathom (13.82 °N, 100.04 °E) in the lowland central region near Bangkok, and Songkhla (7.20 °N, 100.60 °E) in the peninsular southern region with low pollution.

Various components of solar radiation are routinely monitored at each station, including direct normal irradiance, direct normal illuminance, diffuse horizontal irradiance and diffuse horizontal illuminance. For each station, a luxmeter (EKO, model ML-020S-O) equipped with a shade ring (Kipp&Zonen, model 121) is employed to measure diffuse illuminance and a pyranometer (Kipp&Zonen, model CM 11) equipped with a shade ring (Kipp&Zonen, model 121) is used to measure diffuse irradiance. At Chiang Mai, Ubon Ratchathani and Songkhla stations direct normal irradiance is monitored using a Kipp&Zonen pyrheliometer (model Ch1) equipped with a two axis sun tracker (Kipp&Zonen, model 2AP). The pyrheliometer fabricated by Eppley (model NIP) equipped with the sun tracker (Kipp&Zonen, model 2AP) is used to measure direct normal irradiance at Nakhon Pathom station. For all stations, luxmeters (EKO, model ML-020S-O) each equipped with a collimator have been recently purchased and placed on the same sun tracker as that of the pyrheliometer so as to measure direct normal illuminance. Global irradiance and illuminance are also measured using Kipp&Zonen pyranometers (model CM11) and EKO luxmeters (model ML-020S-O), respectively at the four stations and the data obtained from the measurements are used as references for data screening procedure.

All recorded data are sent to our laboratory at Silpakorn University in Nakhon Pathom by email once a month. At the laboratory, voltage data from the pyranometers, pyrheliometers and luxmeters are converted into solar irradiance and illuminance using the corresponding responsivities of these instruments. All irradiance and illuminance data are subjected to quality control process by using the guideline of CIE (Commission Internationale de l'Eclairage) [30]. The quality control procedure includes screening the data for unrealistic conditions such as direct illuminance being greater than the extraterrestrial illuminance or diffuse illuminance being greater than global illuminance measured at the same stations.

The pyranometers and luxmeters at the four stations are calibrated yearly using a traveling pyranometer and luxmeter recently calibrated at the manufacturers. All pyrheliometers are calibrated against an HF absolute cavity pyrheliometer which is traceable to the 10th and 11th International Pyrheliometer Comparison at Davos, Switzerland. The four stations are equipped with Cimel sunphotometer (model CE318) which are used to measure the solar spectral radiance at wavelengths of 340, 380, 440, 500, 675, 870 and 1020 nm. These sunphotometers belong to our laboratory and are part of the Aerosol Robotic Network (AERONET) of NASA [31]. The spectral data from these sunphotometers are routinely processed by AERONET (http://aeronet.gsfc.nasa.gov) to provide aerosol optical properties and precipitable water and are used in the modeling of luminous efficacies. The sunphotometers are regular calibrated by AERONET. All instruments are maintained by well-trained officers at the stations. The measurements and data are summarized in Table 1. The location of the four stations and the pictorial views of the station instruments are shown in Fig. 1.

2.2. Satellite-based data

Cloud information is obtained from the digital data retrieved from the visible channel of the MTSAT-1R satellite for the period: 2007–2011. The data are displayed as images covering the entire area of Thailand, with a spatial resolution of 3 × 3 km^2. These images are transformed to cylindrical projection and then navigated using the coastline as reference. Nine pixels centered at the position of each station are selected from the image and averaged to represent the gray level of these stations (Fig. 2). The gray level is further converted into the earth-atmospheric reflectivity (ρ_{EA}) and is used to derive the cloud index as explained in the next section.