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A technique to map monthly average global illuminance from satellite data in the tropics using a simple semi-empirical model

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ABSTRACT

This paper presents a technique to map monthly average hourly global illuminance from satellite data. A semi-empirical model relating monthly average global illuminance to cloud index, precipitable water, total ozone column (TOC), aerosol optical depth (AOD) and air mass was developed. Data for the cloud index, AOD and TOC were obtained from the visible imagery data of MTSAT-1R, MODIS/Terra and OMI/Aura satellites respectively, while precipitable water was extracted from NCEP/NCAR reanalysis database. The model was formulated using global illuminance measured at four stations in Thailand for a four-year period and validated with an independent one-year data set. Values of monthly average hourly global illuminance calculated from the model and those obtained from the measurements were in good agreement, with a root mean square difference (RMSD) and mean bias difference (MBD) of 8.1% and −0.8%, respectively. The model was used to calculate monthly average hourly global illuminance over Thailand and the results were displayed as illuminance maps. The maps reveal diurnal and seasonal effects mainly in response to solar zenith angle changes and cloud cover related to the southwest and northeast monsoons.

1. Introduction

It has been well recognized that daylight is abundant in the tropics [1]. As a result, a number of daylight-integrated buildings and daylight equipment have been developed for the tropics [2–6]. In general, to design a daylight-integrated building at a location, information on its daylight environment is usually required. One such data is daylight illuminance. Ideally, illuminance data should be obtained from a dense network of daylight stations. However, due to cost, the number of daylight stations is still limited and illuminance data need to be obtained using a modeling approach. Although, a number of authors have proposed luminous efficacy models for estimating illuminance from irradiance [7–10], measurements of irradiance in the world are also limited.

As illuminance is part of broad-band solar radiation which is derivable from satellite data [11–16], it is possible to estimate illuminance from satellite data. The advantage of this satellite technique is that illuminance data can be obtained for all areas corresponding to satellite pixels. The first attempt in estimating illuminance from satellite data was conducted in the SATEL_LIGHT project [17]. Later on, our research group proposed a physical approach for calculating global illuminance from satellite data [18] and displayed the results as illuminance maps. A similar approach has been proposed by He and Ng [19]. Such a physical, albeit complex, approach is general. At the other extreme, empirical statistical relationships may be derived [20]. But they lack generality and their application in some environments may be questioned. In this study, we propose a simple technique to estimate global illuminance from satellite data using a semi-empirical model and the estimated illuminance is displayed as illuminance maps. The study is applied to the tropical environment of Thailand. In this environment, water vapor content is high in the wet season owing to the southwest monsoon [21] and aerosol load is high in the dry season mainly due to biomass burning [22].

As cloud has a random nature in terms of structure and optical properties, it is difficult to calculate hourly global illuminance using 1-2 satellite images per hour. However, cloud regional structure emerges after daily or longer term averaging. In this study, we choose to map monthly average hourly illuminance. The resulting maps provide a climatology of illuminance which is useful for evaluating daylighting potential over the areas of interest.

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2. Methodology

The approach proposed in this work consists of the acquisition of data, formulation of a satellite-based illuminance model, model validation and illuminance mapping. Details are described as follows.

2.1. Acquisition of data

2.1.1. Ground-based data

Illuminance data were obtained from a network of four solar monitoring stations established and operated by our group. These are Chiang Mai (18.78°N, 98.98°E), Ubon Ratchathani (15.25°N, 104.87°E), Nakhon Pathom (13.82°N, 100.04°E) and Songkhla (7.20°N, 100.60°E) (Fig. 1). At each station, a luxmeter (EKO, model ML-020-O) was used to measure global illuminance. The voltage signal from the luxmeter was captured by a datalogger (Yokogawa, model DC100) with a sampling rate of 1 s. The signals were averaged every 10 min and the averaged value was recorded in the memory of the datalogger. The recorded data were sent to our laboratory once a month where they were converted into global illuminance using the responsivity of the luxmeter. The 10 min data were averaged to obtain hourly data. These data were used in the model formulation and validation.

2.1.2. Satellite-based data

Cloud state is the main factor affecting global illuminance and it was derived from imagery data of the visible channel of the MTSAT-1R satellite. The data comprises nine hourly images per day (8:30–16:30), encompassing a five-year period (2007–2011). These satellite data were processed using a method similar to that described in our previous work [18]. Each final image consists of a matrix of 500 × 800 pixels with a spatial resolution of 3 × 3 km^2. Each pixel is characterized by a value of the earth-atmospheric reflectivity (ρ_{EA}). The algorithm selects a matrix of 3 × 3 pixels centered at the illuminance measuring stations and extracts it. Then a cloud index (n) at each pixel in the matrix was calculated from a formula proposed by Cano et al. [23] and it is written as:

$$n = \frac{\rho_{EA} - \rho_G}{\rho_C - \rho_G} \tag{1}$$

where ρ_{EA}, ρ_G and ρ_C are the earth-atmospheric reflectivity, ground reflectivity and maximum cloud reflectivity, respectively. The ground reflectivity was derived from cloud-free satellite images employing the method proposed by Janjai et al. [24]. The maximum cloud reflectivity was computed from the maximum value of the gray level of the satellite images. The final step involves averaging all estimates of the 9 matrix array so as to obtain one value of n.

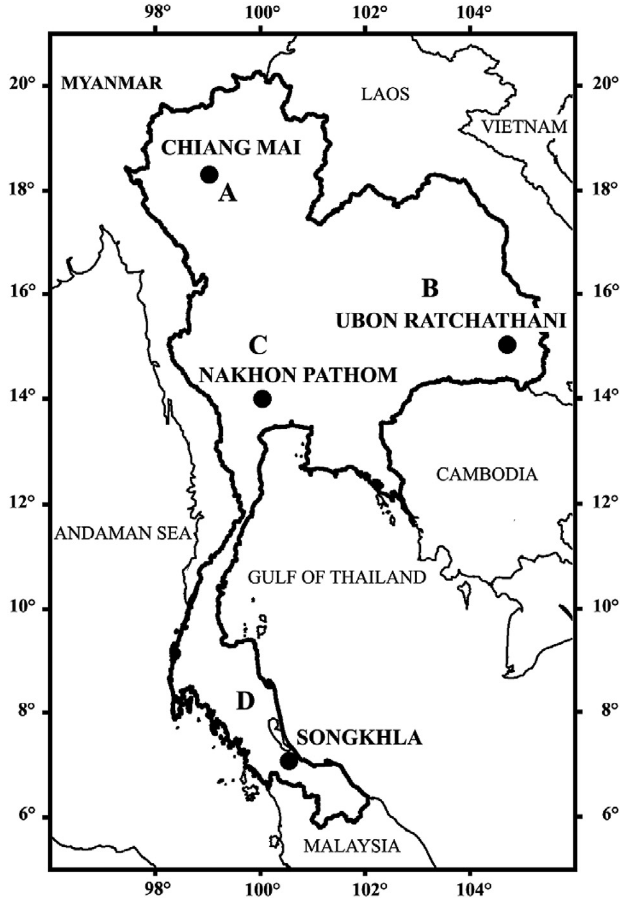

Fig. 1. Locations of the measuring stations at Chiang Mai, Ubon Ratchathani, Nakhon Pathom and Songkhla. A, B, C and D indicates the main regions of the country, namely the northern region, northeastern region, central region and the southern region, respectively.

As aerosol, ozone and water vapor affect surface global illuminance, these atmospheric constituents were also acquired. Aerosol was quantified by aerosol optical depth (AOD) and data on AOD at 500 nm were taken from MODIS/Terra satellite. They were downloaded from a website of NASA: ftp://ladsweb.nasacom.nasa.gov/allData/51/MOD08_D3/. The data obtained from the website were interpolated to fill all spatial gaps. Then the values of AOD at the position of the four ground-based stations were extracted for use in this work. From MODIS data set, AOD in Thailand typically varies in the range of 0.01–0.8, being high in the dry season due to biomass burning and low in the wet season. Wang et al. [25] reported that AOD from MODIS over arid and semi-arid regions has large errors and the AOD from MODIS over farmland gives reasonable accuracy. As Thailand is located in the tropics and most surfaces are covered by green vegetation year round, the accuracy of AOD derived from MODIS is expected to be similar to the case of the farmland.

The total ozone column (TOC) and precipitable water (w) were used to quantify the effect of ozone and water vapor, respectively. TOC was derived from OMI/Aura satellite (ftp://toms.gsfc.nasa.gov/pub/omi/data/ozone/) while precipitable water data from NCEP/NCAR reanalysis database (ftp://ftp.cdc.noaa.gov/Datasets/ncep.reanalysis.dailyavgs/surface/) were acquired for this work. A similar procedure to that of AOD was used to extract TOC and precipitable water data at the four stations.

In general, precipitable water from NCEP/NCAR data set has errors less than 20% in tropical sites [26]. For TOC derived from OMI/Aura, its accuracy is globally better than 1% [27]. In Thailand typical range of values of TOC is 230–280 DU while the typical range of precipitable water is 2.5–7.0 cm. From NCEP/NCAR data set and OMI/Aura data set, the ranges of precipitable water and TOC are comparable with other tropical regions.

Both ground- and satellite-based data were separated into two data sets. The first set encompassing a four-year period (2007–2010) was used to build a semi-empirical model and the second set (2011) was used for model validation.

2.2. Formulation of the model

Based on information on the spectrum of extraterrestrial solar radiation [28] and the absorption and scattering characteristics of various atmospheric constituents [29], solar illuminance at the earth's surface may be expressed as a function of water vapor, total ozone column, aerosol optical depth and cloud cover. To obtain surface solar illuminance, physical or empirical approaches can be