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An investigation of the performance of 14 models for estimating hourly diffuse irradiation on inclined surfaces at tropical sites

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A B S T R A C T

The performance of 14 models for estimating hourly diffuse irradiation on inclined surfaces was investigated. In order to obtain solar radiation data for this investigation, equipment for measuring solar radiation on inclined surfaces facing to the north, south, east and the west at different tilted angles to the horizontal surface (30°, 60° and 90°) were constructed and installed at two tropical sites in Thailand, namely Nakhon Pathom (13.82 °N, 100.04 °E) and Ubon Ratchathani (15.25 °N, 104.87 °E). Radiation data encompassing different periods of 1–4 years were used in this work. Diffuse irradiance measurements at different tilted angles were compared with various model algorithms. Results show that the Muneer and Gueymard models have comparable performance in terms of root mean square difference (RMSD) and these models give the lowest RMSD, as compared to that of the other models.

1. Introduction

Solar radiation data are of importance for designing energy-efficient buildings, where they are typically used in such applications as calculating solar heat gains or cooling loads. Apart from solar applications to building design, they also provide input data for a solar energy collecting device, an important component of systems which acquire solar energy. In general, solar radiation data are obtained from meteorological or solar monitoring stations where solar radiation is routinely measured. Most stations record global radiation on a horizontal surface and data for tilted or vertical surfaces are extremely sparse. However, global solar radiation on vertical surfaces are usually required for building applications. For solar energy use, solar energy collecting devices such as flat plate solar collectors and solar cell modules, are usually mounted on inclined surfaces and global radiation on such surfaces is generally required for performance assessment of these devices. Due to these needs, modeling approaches have been developed for converting global radiation on a horizontal surface into a corresponding quantity on an inclined surface.

As global radiation consists of direct and diffuse components, the conversion of these components on inclined surface are normally carried out separately. These two components are added up so as to obtain the total or global radiation on the inclined surface. The conversion of direct radiation is straight forward and it is common to use a conversion factor which is a function of geometrical parameters of the inclined surface and the position of the sun [1]. The most difficult task is the conversion of horizontal diffuse radiation from the sky into the inclined surface. The reason is that diffuse radiation from the sky depends strongly on sky conditions which vary with various atmospheric parameters and meteorological conditions.

On first principles it is possible to define diffuse radiation incident on a tilted plane (I_{dT}) with the incident angle i in terms of radiance from the sky (R_s) and ground (R_g) surface:

$$I_{dT} = \int_{sky} R_s(\theta, \phi)\cos(i)d\Omega_{sky} + \int_{ground} R_g(\theta, \phi)\cos(i)d\Omega_{ground} \quad (1)$$

Contributions come from the sky (first term) and ground (second term). For the contribution from the sky, sky radiance (R_s) is a function of its position in the hemisphere, indicated by zenith θ and azimuth ϕ, as is ground radiance (R_g). The total irradiance on the tilted surface is obtained by integrating the product of the sky radiance by the cosine of the incidence angle over all solid angles containing sky (Ω_{sky}). Similarly, the contribution from the ground (second term) is the integration of the product of the ground radiance (R_g) by cos (i) over the solid angle Ω_{ground}. As it stands, I_{dT}

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is strongly dependent on surface properties of the ground so it is difficult to generalize any measurement results. A common approach is to use a black metal surface which essentially blocks contributions from the ground, therefore eliminating the second term in Eq. (1).

A further simplification to Eq. (1) follows if sky radiance is assumed isotropic, i.e. independent of θ or ϕ. Radiance R_s may be taken out of the integral so that Eq. (1) reduces to

$$I_{dT} = R_s \int_{sky} \cos(i) d\Omega_{sky} = \pi R_s \frac{(1+\cos\beta)}{2} \quad (2)$$

where β is the tilt angle of the tilted surface relative to the horizontal surface. Note that when $\beta = 0$, the surface is horizontal and Eq. (2) reduces to $I_{dh} = \pi R_s$. A convenient form is to express I_{dT} in terms of I_{dh}:

$$I_{dT} = I_{dh} \frac{(1+\cos\beta)}{2} \quad (3)$$

Eq. (3), originally presented by Liu and Jordan [2] has formed the basis of numerous studies over the years. Modifications are needed as radiance from the sky hemisphere is not isotropic. Table 1 summarizes the main approaches. Karonakis [3] and Badescu [4] changed the coefficient constants in Eq. (3) to accommodate increased radiance from the southern portion of the sky in the northern hemisphere. More specific treatment for anisotropy involves various parameters, mainly θ, the angle between the normal to the surface and the solar zenith angle (Bugler [5]; Klucher [6]; Gueymard [7], Temps and Coulson [8]), or a conversion factor $r_b = \max\left(0, \frac{\cos\theta}{\cos\theta_Z}\right)$ where θ_Z equals the solar zenith angle (Hay [9]; Willmott [10]; Ma and Iqbal [11]; Skartveit and Olseth [12]; Reindl [13]; Muneer [14]). Some authors have also examined increased radiance contributions from the sky zone near the horizon (Temps and Coulson [8]; Klucher [6]; Reindl [13]; Perez et al. [15]).

Atmosphere turbidity from clouds and aerosols tends to discourage variability in sky radiance, resulting in close to isotropic conditions in thick overcast cloud cover. Several turbidity indices have been used, such as the ratio of diffuse I_{dh} to global I_{gh} horizontal irradiance [6], the ratio of measured direct horizontal irradiance I_{bh} to the extra-terrestrial horizontal irradiance, I_{0h} [9–14]. Other authors, for example Perez et al. [15] used turbidity and clearness indices which in turn are a function of direct and diffuse horizontal irradiance as well as the extra-terrestrial irradiance. A different approach has been taken by Gueymard [7] who represented the irradiance on the tilted surface as being contributed by a cloudy and cloudless portion of the sky hemisphere.

From the above discussion, it is evident that a range of factors influence I_{dT} requiring measurement and validation in a wide range of environments before a particular expression is used. In particular, little work has been conducted in tropical regions where sky conditions and solar angles are different from those experienced in mid- and high-latitude studies. The tropical environment of Thailand is characterized by more frequent cumulonimbus clouds in the rainy season and high aerosol loads during the dry season [16] as a result of biomass burning. In addition, the sun at noontime is mostly overhead. These processes affect the magnitude and isotropy of the diffuse radiation from the sky. Therefore, the objective of this work is to evaluate the performance of 14 slope irradiation models using extensive experimental data collected at two sites in Thailand using different sensor tilt angles and azimuthal orientations.

2. Experimental set up

The performances of various models described in Section 1 were evaluated in an experimental program conducted in Nakhon Pathom (13.82 °N, 100.04 °E) and Ubon Ratchathani (15.25 °N, 104.87 °E). The position of the sites is shown in Fig. 1. Nakhon Pathom and Ubon Ratchathani are located in the central and northeastern parts of Thailand, respectively. They are subjected to a tropical climate. At both locations, there two district seasons, namely the dry season (November–April) and the wet season (May–October). The majority of the sky conditions in the dry season are clear while the conditions in the wet season are cloudy. For each site, a total of 12 pyranometers were positioned at different tilt angles and orientations alongside two pyranometers that measured global and diffuse radiation on a horizontal plane. A painted-black cubic shape box with the dimension of 35 cm × 30 cm × 20 cm was constructed (Fig. 2a). The box was placed on a pole at the height of 1.5 m. A painted black metal plate was horizontally attached to the bottom end of the vertical side to prevent reflected radiation from the ground. The pyranometers are not significantly affected by radiation emitted from the plate as the wavelength range of this radiation is normally out of the range of wavelength response of the pyranometers. Each vertical side of the box was equipped with a pyranometer fabricated by Kipp&Zonen (model CMP6). This equipment was used to measure global radiation incident on the four cardinal vertical surfaces (N, S, E, W), corresponding to the azimuthal angle (γ) 180°, 0, 90° and −90°, respectively [1]. Two additional pyranometers were used for each cardinal orientation at tilt angles of 30° and 60° for a total of eight measurements in addition to the four oriented in the vertical (Fig. 2b).

At each site, global and diffuse radiation is also acquired and the instruments are regularly maintained by our laboratory. Global and diffuse radiation is measured using CM11 Kipp&Zonen pyranometers, which also include a shade ring (Kipp&Zonen, model CM121) for the second pyranometer measuring diffuse radiation. Data from these instruments have also been used in this work. All measuring instruments of each site were installed on a roof-top of a building, which is mostly free from any obstructions.

The voltage signals from all pyranometers were captured every 1 s by a data logger (Yokogawa, model DC100). These were averaged over a 10 min period and further stored in the memory of the data logger. The data were transferred to our laboratory once a month. At the laboratory, the averaged signals were converted into irradiance using the responsivity of the pyranometers. The 10-min irradiance was integrated to obtain hourly irradiation in MJ m^{-2}. All pyranometers are annually calibrated against a reference pyranometer using the procedure described in the International Organization for Standardization [17]. The reference pyranometer is a pyranometer (Kipp&Zonen, model CM11) which was calibrated against an absolute cavity pyrheliometer (Eppley, number AHF36013) and this pyrheliometer had been calibrated at the World Radiation Center in Davos, Switzerland. The quartz domes of the pyranometers are regularly cleaned. All instruments are maintained by well trained officers at the sites. The effect of the shade ring on diffuse irradiance was corrected using a correction table provided by the manufacturer. The details of measurements and the period of data used in this work are presented in Table 2.

According to the specification the calibration of the pyranometers, the uncertainty of the pyranometer measurements was estimated to be less than 5%.

3. Data processing

Prior to the use of data, all irradiation data were subjected to a