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Predicting daylight illuminance and solar irradiance on vertical surfaces based on classified standard skies

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A B S T R A C T

Solar irradiance and outdoor illuminance, particularly on vertical surfaces are crucial to energy-efficient building designs and daylighting schemes. In Hong Kong, only hourly horizontal global solar radiation data have been systematically recorded for a long period but no measurements of daylight illuminance exist. In 2003, the International Commission on Illumination (CIE) adopted a range of 15 standard skies covering the whole probable spectrum of skies in the world. Standard skies of the same category would have the identical well-defined sky radiance and luminance distributions. Once the skies are identified, the basic solar irradiance and daylight illuminance at the surfaces of interest can be obtained, involving simple mathematical expressions. This study presents a numerical approach to predict the vertical solar irradiance and daylight illuminance based on the CIE standard skies. Climatic parameters recorded between January 2004 and December 2005 are used in the analysis. The performance of the calculation method is evaluated against data measured in the same period. The annual RMSEs were found ranging from 17.7% to 20.8% for daylight illuminance prediction and 17.9%–19.8% for solar irradiance estimation. The findings provide an alternative to compute solar irradiance and daylight illuminance on vertical surfaces facing various orientations.

1. Introduction

Daylighting is an effective and sustainable development strategy for enhancing visual comforts [1] and displacing the need for high grade energy (electricity) used for artificial lighting [2–6]. It has been reported that proper daylighting schemes could improve health and physical development [7]. Sky irradiance is essential to energy-efficient building designs and the development of active and passive solar energy systems. For estimating building envelop cooling loads and the corresponding capacity of air-conditioning equipment, solar heat gain data are required [8]. A prerequisite to the design of solar electric and solar thermal applications is the availability of sky irradiance at that location. The availability of measurements is the most effective and accurate way of setting up such databases. There are great demands for obtaining daylight illuminance and sky irradiance on vertical surfaces particularly for high-rise curtain buildings [6,9–13]. In Hong Kong, only horizontal solar radiations have been systematically recorded by the Hong Kong Observatory as part of its routine work but no measurements of outdoor illuminance.

Due to the strong forward-scattering effect of aerosols, the sky-diffuse component is anisotropic. An accurate estimation of the available sky irradiance and daylight illuminance includes not just the total intensity of irradiance and light coming from the sky but also their distribution over the sky vault. In the absence of measurements, the common approach for predicting the components on inclined surfaces is based on horizontal measurements [14,15]. Alternatively, the sky irradiance and daylight illuminance on a sloping plane can be computed by sky radiance and luminance models [16,17], respectively, or by integrating the radiance and luminance distributions of the sky 'viewed' by the plane [18,19]. However, radiance and luminance data for the whole sky vault are far from being widely available. Recently, the International Commission on Illumination (CIE) has adopted a list of 15 standard skies [20]. Each sky standard represents a unique well-defined sky luminance pattern expressed by simple mathematical equations. The luminance distribution for every CIE sky can help the determination of daylight illuminance on inclined surfaces, in particular the vertical planes facing various orientations.

Daylight is the visible part of solar radiation. The same calculation procedures for computing daylight illuminance from classified standard skies can also be applied to predict sky irradiance. A number of researchers have pointed out that the 15 CIE Standard

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Skies provide a good overall framework for representing the actual sky conditions [21,22]. There are many appropriate climatic parameters to interpret daylight climates and sky conditions [23,24]. Previously, we identified the 15 CIE Standard Skies using various suitable climatic variables and methods [25–29]. This work estimates the vertical sky irradiance and daylight illuminance data based on the classified standard skies. An error analysis of the proposed approach is reported. Characteristics of the findings are discussed.

2. CIE Standard Skies and useful daylight parameters

Each standard sky luminance distribution is described as a combination of gradation and indicatrix functions [30].

$$L = L_Z \frac{f(\chi)g(Z)}{f(Z_S)g(0^\circ)} \tag{1}$$

$$\frac{g(Z)}{g(0^\circ)} = \frac{1 + a\ \exp(b/\cos Z)}{1 + a\ \exp\ b} \tag{2}$$

$$\frac{f(\chi)}{f(Z_S)} = \frac{1 + c[\exp(d\chi) - \exp(d\pi/2)] + e\ \cos^2\chi}{1 + c[\exp(dZ_S) - \exp(d\pi/2)] + e\ \cos^2 Z_S} \tag{3}$$

where L is the sky luminance in an arbitrary sky element (cd m^{-2}); L_z is the sky luminance at the zenith (cd m^{-2}); Z is the zenith angle of a sky element (rad); Z_s is the zenith angle of the sun (rad) and χ is the scattering angle (rad) (i.e. shortest angular distance between the sky patch and the center of the sun) $=$ acrcos($\cos Z_s \cdot \cos Z + \sin Z_s \cdot \sin Z \cdot \cos|\phi - \phi_s|$); ϕ is the azimuth angle of the sky element (rad); ϕ_s is the azimuth angle of the sun (rad); a, b, c, d and e are adjustable coefficients.

The standard gradation function changes the sky luminance between the horizon and the local zenith with the largest luminance being at the zenith under overcast skies but reverses for clear skies with a brighter horizon. The scattering indicatrix denotes the sunlight scattering in the atmosphere. The maximum luminance appears near to the solar position, decreasing rapidly with the distance from the sun [30]. Both gradation and indicatrix functions are of 6 types. The combinations can yield 36 skies [31] but only 15 of those were adopted to become standard skies.

The original criterion to define the CIE Standard Skies is the ratio of the zenith luminance to the horizontal diffuse illuminance (L_z/D_v). As L_z is the major component contributing to D_v, a good correlation should be between these two daylight parameters. The L_z/D_v ratio can directly be computed from the gradation and indicatrix functions for each sky standard and its variation is dependent on solar altitude (α_s) except under 'dark' overcast skies [23] with unity indicatrix. Theoretically, the 15 L_z/D_v curves can differentiate from each other between skies at $\alpha_s \leq 35^\circ$ with the distinct values ranging between 0.1 and 0.41 [32]. However, the 15 curves are not parallel but intersect with each other at around $\alpha_s \leq 35^\circ$. For places where α_s often exceeds 35°, using L_z/D_v to classify the standard sky can lead to ambiguous results [33,34]. Other climatic elements including the ratio of horizontal global illuminance (G_v) and D_v to the corresponding horizontal extraterrestrial illuminance (i.e. G_v/E_v and D_v/E_v) and the luminous turbidity (T_v) are appropriate to distinguish daylight climate [35]. When the atmosphere is clear, a small portion of daylight illuminance is scattered, giving in a predominant direct component with a large amount of G_v/E_v. For an overcast sky, natural light is mainly scattered, showing a large portion of diffuse component with a small G_v/E_v result. As the whole sky is being considered, D_v is an appropriate climatic variable to indicate the sky condition. Large D_v/E_v values often appear on partly cloudy days. For relative low D_v/E_v data, they may represent overcast and clear skies. Once the 3 typical skies (i.e. overcast, partly cloudy and clear) have been interpreted, D_v/E_v can then be used to further differentiate overcast and clear sky standards. The attenuation of luminous solar energy through an atmosphere gives an indication of T_v [36]. For clear skies, T_v relates the atmospheric transmittance in the direction of the direct sunlight to overall skylight efficiency [37]. Various T_v values can be adopted to distinguish between clean and polluted cloudless skies [38]. The criteria for classifying the 15 CIE Standard Skies using these daylight variables (i.e. L_z/D_v, G_v/E_v, D_v/E_v and T_v) can be found in our previous work [26] and they are summarized as follows.

Firstly, classify into the three typical sky conditions (i.e. overcast, partly cloudy and clear) using the pair L_z/D_v–G_v/E_v hybrid daylight variable with the criteria as below:

- Overcast skies: $L_z/D_v \geq 0.3$ and $G_v/E_v \leq 0.3$
- Partly cloudy: $0.17 < L_z/D_v < 0.3$ and $G_v/E_v \leq 0.3$ or $L_z/D_v > 0.17$ and $0.3 < G_v/E_v < 0.5$
- Clear: $L_z/D_v \leq 0.17$ or $L_z/D_v \geq 0.17$ and $G_v/E_v \geq 0.5$

Distinguish between the 5 types under the overcast skies dataset:

- Identify sky no. 5 when $L_z/D_v < 0.32$
- Categorize sky nos. 1 & 3 when $D_v/E_v < 0.18$ and sky nos. 2 & 4 when $D_v/E_v \geq 0.18$
- Differentiate sky no. 1 when $L_z/D_v \geq 0.38$ and sky no. 3 when $L_z/D_v < 0.38$
- Classify sky nos. 2 and 4 by comparing with the corresponding theoretical L_z/D_v curves with the nearest value

Distinguish between the 5 types under the partly cloudy skies dataset:

- Single out sky no. 6 when there is no direct-beam component
- Categorize sky nos. 7 & 9 when $T_v \geq 12$ and sky nos. 8 & 10 when $T_v < 12$
- Identify sky nos. 7 and 9 by comparing with the corresponding theoretical L_z/D_v curves with the nearest value
- Classify sky nos. 8 and 10 by comparing with the corresponding theoretical L_z/D_v curves with the nearest value

Distinguish between the 5 types under the clear skies dataset:

- Single out sky no. 12 when $T_v \geq 4$
- Differentiate sky no. 15 when $D_v/E_v \geq 0.3$
- Classify sky no. 14 by comparing with the corresponding theoretical L_z/D_v curves with the nearest value
- Categorize sky no. 11 when $T_v < 5.5$ and sky no. 13 when $T_v \geq 5.5$

The criterion to classify the sky types 1, 2 3 and 4 using D_v/E_v is based on the typical values listed in Table 2 of the Ref. [30]. The typical D_v/E_v values for sky types 1, 2, 3 and 4 are 0.1, 0.18, 0.15 and 0.22, respectively and D_v/E_v of 0.18 was employed to differentiate sky types 1 & 3 and 2 & 4. The measured L_z/D_v data were used to compare with the theoretical L_z/D_v curves and then classified in the standard sky with the nearest value. Two sky classification approaches are adopted for the study. When the data were recorded at $\alpha_S \leq 35^\circ$, the 15 L_z/D_v theoretical curves are used for categorizing all the 15 CIE Standard Skies [32]. For the data measured at $\alpha_s > 35^\circ$, the above summarized procedures are applied.

With a well-defined sky luminance pattern for an individual standard sky, the daylight illuminance on vertical surfaces facing