DEVELOPMENT OF A SKY RADIANCE DISTRIBUTION MODEL FOR ALL SKY CONDITIONS

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ABSTRACT

In effective use of solar energy and calculation of the heat load of buildings for energy conservation, the actual-state meteorological data are indispensable. It is necessary to propose a sky radiance distribution model, which can correspond to all sky conditions from clear sky to overcast sky. To compose such a model, there should be some index to presume the sky radiance distribution according to the sky condition. In this paper, normalized global irradiance and cloudless index are defined on the basis of measurements as the indices to classify the sky radiance distributions. The relationship between both indices and sky radiance distributions was examined. And an equation of sky radiance distribution for all sky conditions was derived.

KEYWORDS
Sky radiance distribution, Normalized global irradiance, Cloudless index, All Sky Model-R

1. INTRODUCTION

Solar radiation has a great influence on the interior environment of buildings. In many practical applications, sky radiance distribution has been assumed as uniform over the sky hemisphere. But in fact, it varies with sky conditions and other factors. Some model, which reproduces the actual sky conditions, is necessary to be introduced into various calculations. There are some considerations about sky radiance distribution, that is, by Valko, P.[1], Brunger, A.P.[2], Kittler, R.[3], Nakamura, H.[4], Nagata, T.[5], Goto, K.[6] and the others. And some methods of assuming the tilted surface irradiance are proposed. There is no proposal of the numerical equation model which shows the sky radiance distribution continuously for all sky conditions. This study aims to propose a sky radiance distribution model for all sky conditions. For the purpose, the index that classifies the sky condition concerning sky radiance distribution is necessary to compose the model. This paper proposes the sky indices and the equation of sky radiance distribution for all sky conditions named All Sky Model-R.

2. MEASUREMENT OF SKY RADIANCE DISTRIBUTION

Measurements of 1992/3-1993/9 in Tokyo (35°40’ N, 139°49’ E) and 1994/1-1994/12 in Fukuoka (33°31’ N, 130°28’ E) for IDMP (International Daylight Measurement Programme) were applied in this research work. The sky radiance distribution was measured every 15 minutes in Tokyo and every 30 minutes in Fukuoka from sunrise to sunset. The measurement points are 145 points on the sky vault. The sky radiance distribution was measured simultaneously with the sky luminance distribution. It took about three and a half minutes per measurement. Because solar radiation is attenuated by scattering and absorption in atmosphere, the relative optical air mass produces a big influence on the surface irradiance.

Relative optical air mass can be expressed as a function of solar altitude. Thus, all the acquired data are sorted expediently by solar altitude in five-degree intervals. The lowest altitude of sky elements measured for sky radiance is six degrees. Because surrounding buildings influence data at the lowest altitude of sky elements, 30 acquired data at this altitude are excluded from the examination. As a result, the effective number of the data per measurement is 115. The 115 data is called a set by the gross in the below of this paper. In this research work, the data are used for all cases when the solar altitude was higher than five degrees.

3. INDICES TO CLASSIFY SKY CONDITIONS

The global irradiance (*Eeg*) is considered to be a useful index to classify the sky conditions. However, even if the global irradiance is the same, the ratio of the diffuse irradiance (*Eed*) to the global irradiance varies. Therefore, it may be appropriate to use cloud ratio (*Ce=Eed/Eeg*) together with global irradiance to classify sky conditions. However, the global irradiance and the cloud ratio are not free from the dependency on solar altitude. Thus, some new indices that are independent of solar altitude are examined on the basis of global irradiance and cloud ratio.

3.1. Normalized Global Irradiance

The global irradiance is normalized by being divided by the maximum value of the global irradiance that appeared in the same solar altitude. Consequently, this normalized global irradiance is independent of solar altitude. Since such maximum values appear predominantly under the clear sky, there should be a clear sky model defined for global irradiance. There are various clear sky models that are proposed by Bourges, B.[7], Kasten, F.[8], Bird, R.E. and Riordan, C. with SPCTRAL2[9], Gueymard, C. with SMARTS2[10], Rigollier, C.[11] and the others. Various parameters are used in each above-mentioned equation. In particular, the turbidity factor is significant for the clear sky model. Since the daylight turbidity factor is assumed to be 2.45 for CIE Standard Clear Sky, it is suitable to examine the global irradiance when the Linke's turbidity factor is about 2.5. Figure 1(a) shows the clear sky models of global irradiance in comparison when the parameters of each equation are set so that the Linke's turbidity factor is 2.5. As a result of comparison between each equation and measured values, the equation by Kasten, F. was selected for the clear sky model because of its simplicity and was modified a little as follows:

$$Eeg_{cl} = 0.84 \cdot Eeo / m \cdot \exp(-0.027 \cdot TL \cdot m) \quad (1)$$

where Eeg_{cl} is the global irradiance of clear sky [W/m^2], *Eeo* the extraterrestrial normal irradiance [W/m^2], *TL* the Linke’s turbidity factor, and *m* the relative optical air mass[12].

The value of Eqn. 1 with the Linke's turbidity factor of 2.5 was assumed to be the maximum global irradiance. Figure 1(b) shows the maximum global irradiance compared with the measurements in the rage of Linke's turbidity factor from 2.5 to 3.5. The maximum global irradiance almost included the measurements and is defined as the standard global irradiance (*Seeg* [W/m^2]) as follows:

$$Seeg = 0.84 \cdot Eeo / m \cdot \exp(-0.0675 \cdot m) \quad (2)$$

Subsequently, the global irradiance being divided by the standard global irradiance is defined as the normalized global irradiance (*Neeg*).

$$Neeg = Eeg / Seeg \quad (3)$$

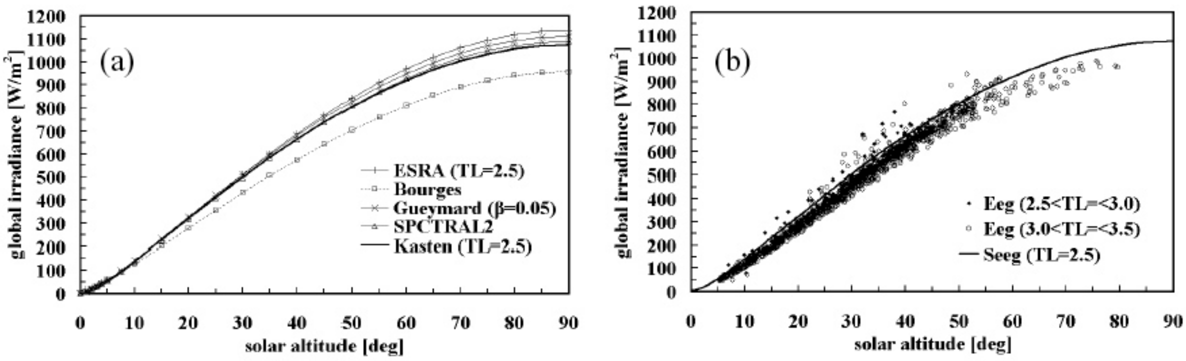

Figure 1: Various global irradiance models (a), and standard global irradiance and measured global irradiances when the Linke's turbidity factor is from 2.5 to 3.5 (b)

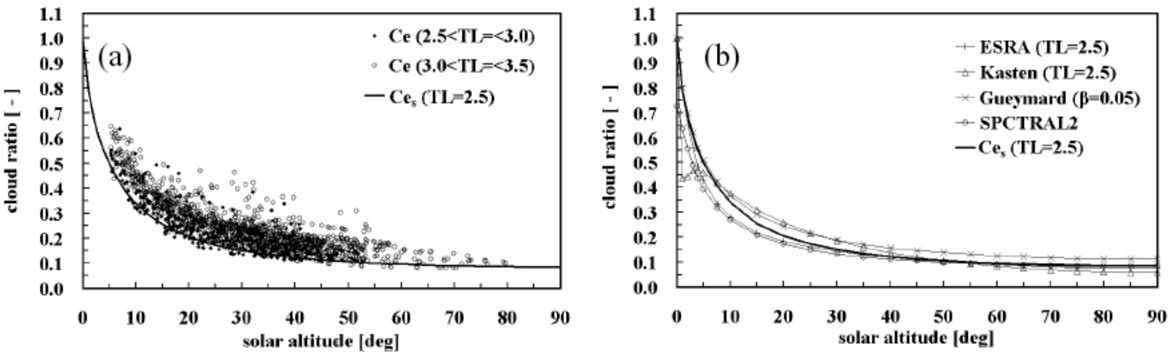

Figure 2: Measured cloud ratios when the Linke's turbidity factor is from 2.5 to 3.5 and the standard cloud ratio (a), and comparison of the cloud ratio between various equations and the standard cloud ratio (b)

3.2. Cloudless Index

The lower boundary values of cloud ratio appear under the clear sky and depend on solar altitude. The cloud ratio with the Linke's turbidity factor of 2.5 was examined as the lowest boundary value. Figure 2(a) shows cloud ratios when the Linke's turbidity factor is from 2.5 to 3.5 and the standard cloud ratio. The minimum value of cloud ratio according to solar altitude was assumed to be a function of relative optical air mass. The standard cloud ratio (Ce_s) was defined as follows:

$$Ce_s = 0.01299 + 0.07698 \cdot m - 0.003857 \cdot m^2 + 0.0001054 \cdot m^3 - 0.000001031 \cdot m^4 \quad (4)$$

Figure 2(b) shows the standard cloud ratio and the cloud ratios calculated from the equation above mentioned. There are slight differences among the calculated values. The standard cloud ratio is an average value of these calculated values. Eqn. 4 is considered to be suitable as the standard cloud ratio. In addition, the following index is defined as the cloudless index (Cle).

$$Cle = (1 - Ce)/(1 - Ce_s) \quad (5)$$

3.3. Classification of Sky Radiance Distributions

The sky radiance distribution can be classified in detail by combining normalized global irradiance and cloudless index like the matrix. Here, classification of sky radiance distributions was tried for all sky conditions by the following procedures.

(1) Data concerning sky radiance distribution and solar radiation are sorted by solar altitude in five-degree intervals.

(2) The normalized global irradiance and the cloudless index are calculated in each solar altitude range, and are classified by 0.1 intervals.
(3) The average sky radiance at each sky element is calculated from the data sets in each category classified by the normalized global irradiance and cloudless index.
(4) The measurements in Tokyo and Fukuoka are classified by the above-mentioned procedure, and average relative sky radiance distributions are prepared.

4. An equation of "All Sky Model-R"

Based on classified average sky luminance distribution data, the regression analysis was repeated. And an equation of sky radiance distribution referred to All Sky Model-R was obtained. The equation is shown as follows in a similar shape to that of the sky luminance distribution.

$$Lea(\gamma_s,\gamma,\zeta) = Lez(\gamma_s)\cdot Le(\gamma_s,\gamma,\zeta) = Lez(\gamma_s)\cdot \frac{\phi(\gamma)\cdot f(\zeta)}{\phi(\pi/2)\cdot f(\pi/2-\gamma_s)} \qquad (6)$$

where $Lea(\gamma_s,\gamma,\zeta)$ is the sky radiance distribution of All Sky Model-R in absolute values [W/m^{2}sr], $Le(\gamma_s,\gamma,\zeta)$ the relative sky radiance distribution to the zenith, $Lez(\gamma_s)$ the zenith radiance [W/m^{2}sr], $\phi(\gamma) = 1 + a/\exp(b\cdot\sin\gamma)$, $f(\zeta) = 1 + c\cdot\{\exp(d\cdot\zeta) - \exp(d\cdot\pi/2)\} + e\cdot\cos^2\zeta$, $a = 9.25/[1+0.29\cdot\exp(3.51\cdot Ri)] - 1.16$, $b = 0.927/[1+8.94\cdot\exp(-2\cdot Ri)] - 1.16$, $c = 1.7\cdot(0.94\cdot Ri)^{3.2}\cdot\exp(1.04\cdot Ri)\cdot(2.3-Ri)^{1.63}$, $d = -3.5/[1+8.6\cdot\exp(-2.3\cdot Ri)]$, $e = 0.56/[1+89\cdot\exp(-3.95\cdot Ri)]$, $Ri = Neeg + Cle^{0.5}$ the radiance index, γ_s the solar altitude [rad], γ the altitude of a sky element [rad], and ζ the angular distance between the sun and the sky element [rad].

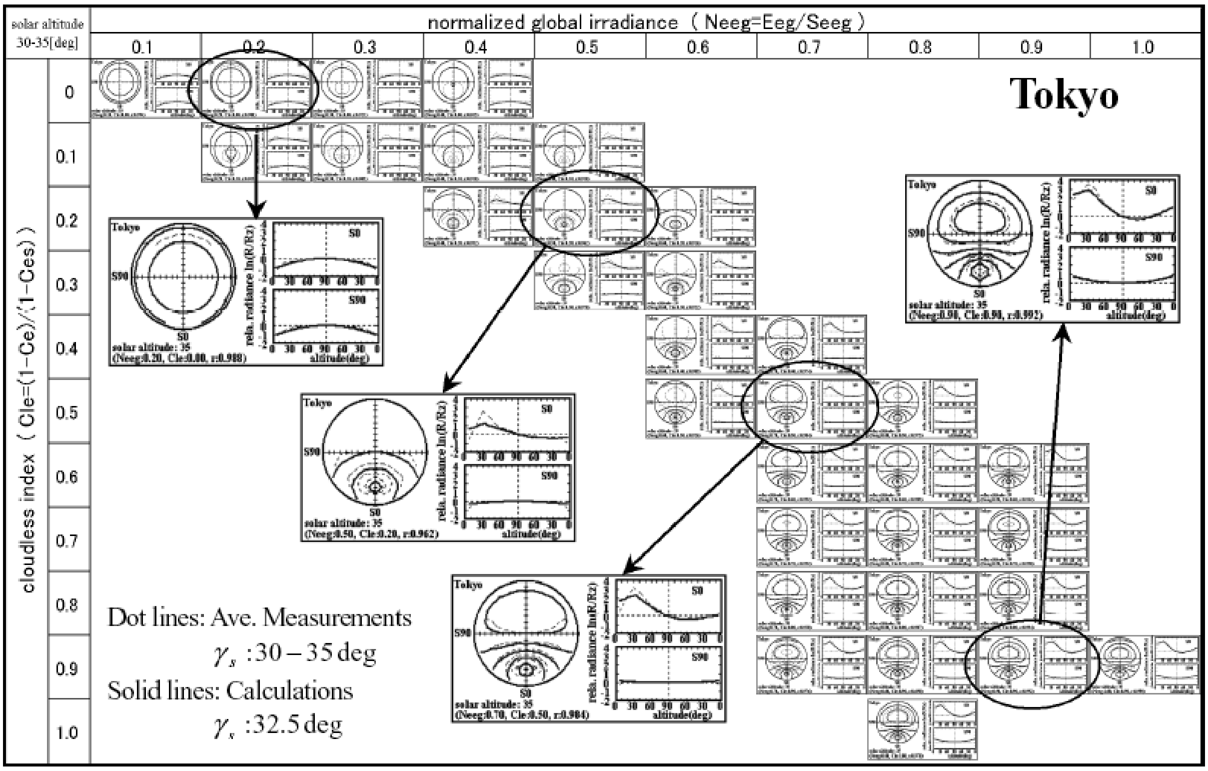

Figure 3: Relative sky radiance distributions between average measurements and calculations

The zenith radiance is obtained as follows:

$$Lez(\gamma_s) = Eed \Big/ \int_{\gamma=0}^{\pi/2}\int_{\alpha=0}^{2\pi} \mathrm{Le}(\gamma_s,\gamma,\zeta)\cdot\sin\gamma\cdot\cos\gamma\cdot d\gamma\cdot d\alpha \qquad (7)$$

Figure 3 illustrates comparisons of relative sky radiance distributions between measurements in Tokyo in the range of solar altitude from 30 to 35 degrees and calculations at the solar altitude of 32.5 degrees. The calculation values correspond with the measurement values very well. There is also good correspondence with the measurements in Fukuoka.

5. VALIDATION OF "All Sky Model-R"

The vertical irradiances facing north (Eegn), east (Eege), south (Eegs) and west (Eegw) were calculated by All Sky Model-R, and compared with Isotropic Model and Perez Model[13] using the measurements in Tokyo and Fukuoka. The regional and directional RMSEs and MBEs of the calculations are shown in Table 1.

Table 1: Regional and directional RMSEs and MBEs of vertical irradiances calculated [W/m^2]

Model	Site	Root Mean Square Error					Mean Bias Error			
		North	East	South	West	Average	North	East	South	West
All Sky	Tokyo	9.56	16.84	15.81	15.81	16.25	2.07	5.00	2.54	3.76
	Fukuoka	11.86	20.84	19.88	19.36		-5.27	-4.08	1.16	-3.26
Isotropic	Tokyo	38.95	44.09	34.70	43.25	39.85	26.70	8.83	-4.55	8.15
	Fukuoka	30.96	50.22	33.63	43.00		17.59	-5.50	-11.16	-2.25
Perez	Tokyo	20.16	31.96	23.96	29.95	29.21	-9.91	2.02	-6.18	0.23
	Fukuoka	26.32	35.29	29.81	36.24		-17.15	-8.92	-10.54	-6.70

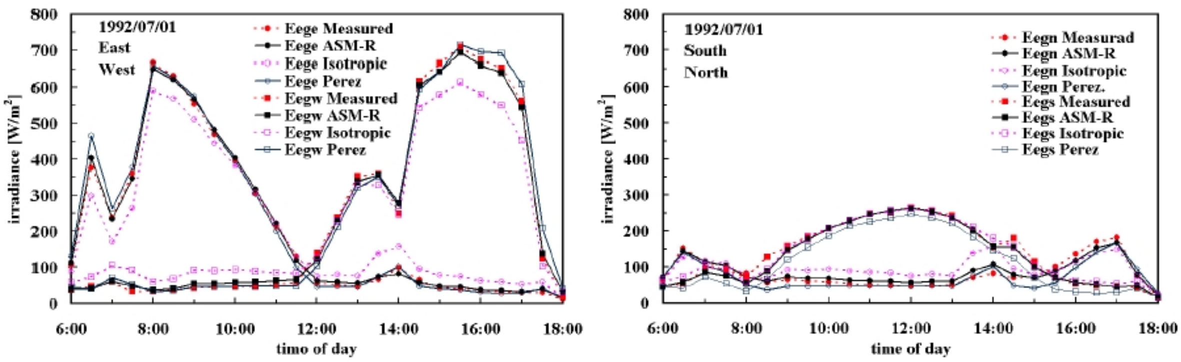

Figure 4: Comparison of vertical irradiances between measurements in Tokyo and calculations (1992/07/01)

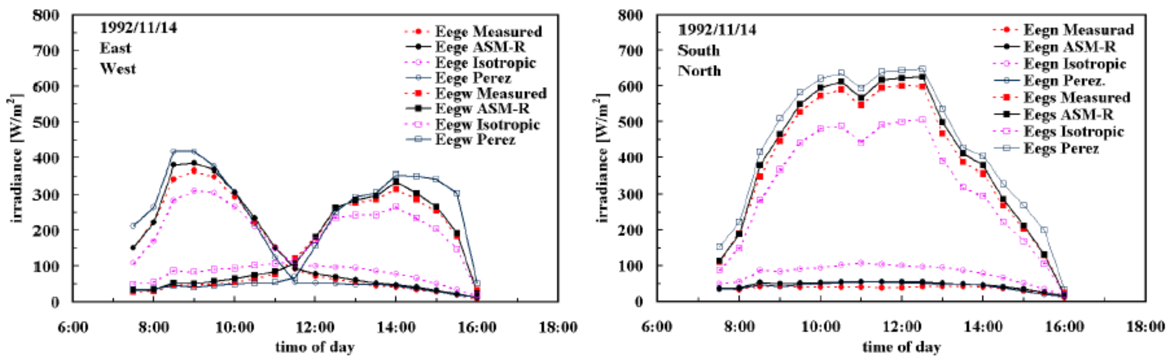

Figure 5: Comparison of vertical irradiances between measurements in Tokyo and calculations (1992/11/14)

For All Sky Model-R, the RMSEs are in the range from 9.56W/m^2 to 20.84W/m^2, and the absolute values of MBE are in the range from 1.16W/m^2 to 5.27W/m^2, which are smaller than those of other models in all conditions.

Isotropic Model has been used to calculate the heat load. The RMSEs range from 30.96W/m^2 to 50.22W/m^2 and the absolute values of MBE range from 2.25W/m^2 to 26.70W/m^2. This model causes large errors and is considered to be insufficient in the future heat load calculation, which should reproduce actual phenomena.

Perez Model is previously accredited with accuracy for the tilted-surface irradiances. The RMSEs range from 20.16W/m^2 to 36.24W/m^2, and the absolute values of MBE range from 0.23W/m^2 to 17.15W/m^2. The errors by Perez Model are smaller than those by Isotropic Model but larger than those by All Sky Model-R.

In all conditions, the RMSEs and MBEs by All Sky Model-R are smaller than those by Isotropic Model and Perez Model. Figure 4 and 5 show comparisons of half-hourly vertical irradiances between measurements in Tokyo and calculations. All Sky Model-R (ASM-R) indicates the accurate estimation values. All Sky Model-R is confirmed to be able to presume the tilted-surface irradiance with high accuracy.

6. CONCLUSIONS

This research aims to propose a numerical equation, which represents the sky radiance distribution for all sky conditions. In this paper, the indices to presume sky radiance distribution were defined, and their relation to the sky radiance distribution was examined, and an equation of the sky radiance distribution for all sky conditions was derived. Sky radiance distributions for all sky conditions are able to estimate by All Sky Model-R based on global irradiance, diffuse irradiance and solar altitude. The result of this research work reproduces the actual sky radiance distributions, and enables detailed prediction of the indoor environment.

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