# CALCULATION OF THE HEATING AND COOLING LOAD OF BUILDINGS USING A SKY RADIANCE DISTRIBUTION MODEL

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## ABSTRACT

We present a model for calculating the sky radiation values considering the sky radiance distribution for a simulated building. We use the sky luminance distribution model of the *CIE standard general sky* rather than the measured sky radiance distribution. In this model, different sky types of the *CIE standard general sky* are identified from values of horizontal global sky radiation *Eeg*, and normal direct solar radiation *Ees* without reference to the measured sky radiance distribution.

To evaluate the model, we calculated 1) the sky radiation values on east, west, north and south-facing vertical surfaces and 2) the annual heating/cooling load of a model room. Three sets of calculations were performed on the assumption of i) uniform sky, ii) measured sky radiance distribution, and iii) sky radiation model. The sky radiation model proposed in this study provides a better estimate of sky radiation values on vertical surfaces and heating/cooling load than estimates derived from a uniform sky model.

## INTRODUCTION

The efficient use and conservation of energy requires accurate predictions of energy consumption. A meteorological model that simulates daylight energy and calculates heating/cooling load within buildings provides a precise prediction of energy use. In the research of such meteorological model, there is a trial of modeling the sky luminance distribution or the sky radiance distribution, which are generally assumed to be uniform in the field of daylight or solar radiation simulation. Some models have already been proposed. The typical models of the sky luminance distribution are shown in the following.

Perez et al., (1990, 1993) proposed a sky luminance distribution model called the All-weather model. This model estimates the relative luminance value of an arbitrary sky element by using five parameters derived from the zenith angle of the sun, *Skyclearness*, and *Skybrightness* (Perez et al., 1990, 1993). Based on the All-weather model, Kittler, Perez (Kittler, R. et al., 1998) modeled the relative sky luminance distribution to the zenith luminance using Gradation and Indicatrix functions. The authors defined 15 sky types that represent outdoor daylight conditions ranging from clear to cloudy sky. The sky types are defined by combinations of the parameter values of the Gradation and Indicatrix functions. The parameter values defining the 15 sky types are determined via data regression by sorting sky luminance data into six classes, with each class containing two functions (Kittler, R. et al., 1998). Kittler et al.'s (1998) model was adopted as the *CIE standard general sky* by the *Commission Internationale De L'eclairage* (CIE).

### CIE Standard General Sky

The *CIE standard general sky* is a model of sky luminance distribution recommended by the CIE. This model represents cloudless skies and skies of homogeneous cloud cover. The relative luminance of the sky element $L_a/L_z$ , whose angular distance from the zenith is $Z$ (*figure 1*), is calculated from formula (1):

$$\frac{L_a}{L_z} = \frac{f(\chi)\varphi(Z)}{f(Z_s)\varphi(0)} \quad (1)$$

$$\varphi(Z) = 1 + a \cdot \exp\left(\frac{b}{\cos Z}\right) \quad (2)$$

$$\varphi\left(\frac{\pi}{2}\right) = 1 \quad (3)$$

$$f(\chi) = 1 + c \cdot \left[\exp(d\chi) - \exp\left(d\frac{\pi}{2}\right)\right] + e \cdot \cos^2 \chi \quad (4)$$

$$f(Z_s) = 1 + c \cdot \left[\exp(dZ_s) - \exp\left(d\frac{\pi}{2}\right)\right] + e \cdot \cos^2 Z_s \quad (5)$$

$$\chi = \arccos(\cos Z_s \cdot \cos Z + \sin Z_s \cdot \sin Z \cdot \cos|\alpha - \alpha_s|) \quad (6)$$

Formulae (2) and (3) represent the Gradation function and formulae (4) and (5) are the Indicatrix function and formula 6 represents the shortest angular distance between a sky element and the sun $\chi$ . The values of parameters *a*-*e* are shown in *Table 6*. The 15 different combinations of the values of the

Gradation function parameters and the Indicatrix function parameters represent the 15 sky types of the *CIE standard general sky* (CIE Standard, 2003).

**Previous work**

We (Hosobuchi, H. et al., 2004) applied the sky types of the *CIE standard general sky*, which is a model of the sky luminance distribution, to values of sky radiance distribution measured at Kyoto University, Japan, and presented the following results:

1) The vertical irradiance value was calculated for the sky type with the lowest *Root Mean Square Error (RMSE)*, which was the difference between measured irradiance values and the value of each sky type. The calculated vertical irradiance values were more precise than those derived from uniform sky calculations.
2) Even where only 5 of the 15 sky types were selected, the increase in relative error of the vertical irradiance value was minor. In comparison with the uniform sky model, the vertical irradiance values were calculated more precisely for these 5 sky types.

**Purpose of the research**

As shown in the previous paper (Hosobuchi, H. et al., 2004), the sky type most similar to the measured sky radiance distribution is determined by the *RMSE* of the sky irradiance value of the 15 sky types and the measurement value. This method requires measurement of the sky radiance distribution in order to calculate the vertical irradiance values. However the sky radiance distribution is rarely measured. If this method is to be widely applied, we need to develop a method of identifying sky type using general meteorological measurements rather than the sky radiance distribution. To achieve this aim, we took the following steps:

1) We examined the relationship between the sky type closest to the measured sky radiance distribution and measured solar radiation (horizontal global sky radiation *Eeg* and normal direct solar radiation *Ees*).
2) Based on the relationships determined at step 1), we developed a method of identifying the sky type on the basis of measured solar radiation *Eeg*, *Ees*.
3) To test the validity of this method, we calculated vertical irradiance values from uniform sky, and compared these values with vertical irradiance values in the south, west, north and east directions as calculated from identified sky type.
4) The heating/cooling load of a model room was calculated using the measured radiance distribution, the uniform sky, and the identified sky type. We also test the validity of applying the value of solar radiation considered the irradiance distribution of the identified sky type to the heating/cooling load simulation.

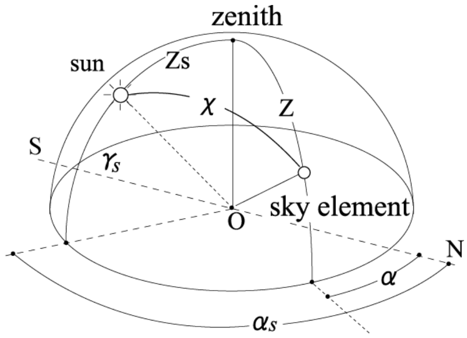



Figure 1 Angles used to define the position of the sun and a sky element

## IDENTIFICATION OF SKY TYPE

In a previous paper (Hosobuchi, H. et al., 2004), we demonstrated that the 5 sky types 1, 8, 13, 14, and 15 are required in order to calculate the vertical irradiance value with adequate precision compared to values calculated from the measured sky radiance distribution. These 5 sky types consist of the combinations of Indicatrix groups 1, 4, 5, 6 and Gradation groups I, III, V, VI.
In this study we do not determine the sky type directly, but use identified Gradation and Indicatrix groups to identify the sky type that best approximates the actual sky conditions.
This method of determining sky type was developed by examining the relationships between the following values of solar radiation, which are the measured meteorological elements:

**i) Indicatrix group**
*Eeg* : Horizontal global sky radiation (mean of 15 minutes measurement)
**ii) Gradation group**
*Ees* : Normal direct solar radiation (mean of 15 minutes measurement)

**Measurement of irradiance value**

Solar radiation data measured at the University of Kyoto by the International Daylight Measurement Programme (CIE-IDMP) from January 1 2001 to December 31 2001 are examined here. Details of the measurement parameters and measuring equipment are shown in *Table1*, and the measurement site is described in *Table 2*.
Prior to data analysis, a quality control test of the data, based on CIE guidelines (CIE, 1994), was applied to the measured values of solar radiation *Eeg* and *Ees*. Those data that failed the test, and accompanying sky radiance distribution measurement data, are excluded from further analysis. Measurement data with a solar altitude of <5° is excluded from analysis because of the influence of adjacent ground objects.

Table 1 Measured parameters and measuring equipment used in this study

| Measurement item | | Measurement equipment | Reference |
|---|---|---|---|
| Sky radiance distribution | [W/m2 sr] | Sky scanner (EKO MS-301LR) | View angle : 11[deg] |
| Sky luminance distribution | [kcd/m2] | | |
| Horizontal sky radiation | [W/m2] | Pyranometer (EKO MS-801) | - |
| | | Shadow band (EKO MB-11) | Radius : 250mm Width : 50mm |
| Horizontal global sky | [W/m2] | Pyranometer (EKO MS-801) | - |
| Normal direct solar radiation | [W/m2] | Pyrheliometer (EKO MS-52) | View angle : 5[deg] |
| | | Sun tracker (EKO STR-02A) | - |
| Outdoor temperature | [ degC] | Thermo couple (T-CC) | - |

Table 2 Details of measurement site

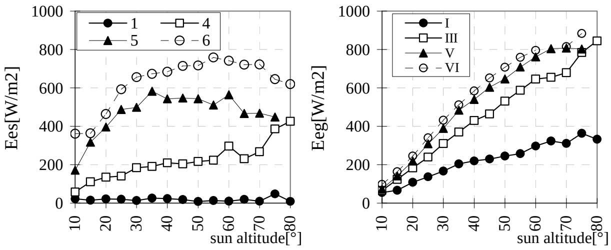
| Mesurement point | Location | Lat. Lon. Al. |
|---|---|---|
| Roof top of Dept. of Architecture Annex, Kyoto Univ. | Yoshida-honmachi, Sakyo-ku, Kyoto-city, Japan | 35°1' N 135°47' E altitude 90m |

Values of solar radiation were measured at 1-minute intervals, while the sky radiance distribution was measured every 15 minutes.

## Indicatrix and Gradation Groups

The relationship between the Indicatrix groups and the values of normal direct solar radiation *Ees* are shown in *figure 2*. The relationship between the Gradation groups and the values of horizontal global sky radiation *Eeg* are presented in *figure 3*.

There is a correlation between the values of solar radiation and the Gradation and Indicatrix groups. For example, values of solar radiation increase in tandem with Indicatrix group data. To indicate these




a) Indicatrix b) Gradation

Figure 4 Mean values of solar radiation at 5˚ bands of sun altitude

relationships more clearly, we calculated the mean solar radiation, at every 5° band of sun altitude, for each Gradation and Indicatrix group (*figure 4*). The data plot generally in order of group number. On the basis of this data we identified the boundaries of Gradation and Indicatrix groups.

## Boundary for identify sky type

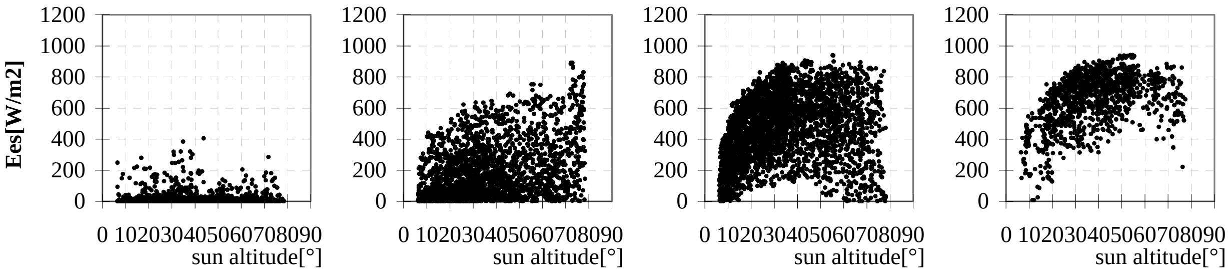
The boundaries between different Gradation and Indicatrix groups were determined in the following way.

1) The mean (ME) and standard deviation (SD) of the values of solar radiation were calculated for every 5° band of sun altitude.

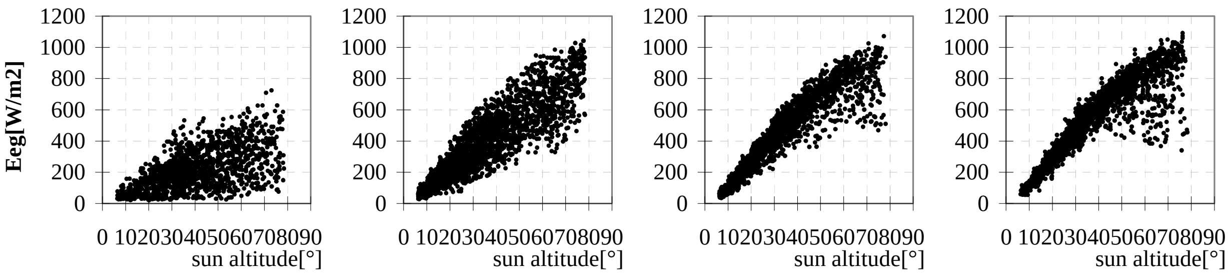
2) Those values of solar radiation greater than ±2SD+ME for every sun altitude band were excluded from further analysis.

3) The means of adjacent bands were averaged at every sun altitude band.

4) In the case that trends reverse (e.g. 80˚ data in *figure 4*), the average calculated at step 3) is ignored and considered missing data.




**a) Indicatrix 1** **b) Indicatrix 4** **c) Indicatrix 5** **d) Indicatrix 6**




**a) Gradation I** **b) Gradation III** **c) Gradation V** **d) Gradation VI**

Figure 3 Relationship between Gradation groups and horizontal global sky radiation

5) Approximate the mean calculated at process 3) with the third polynomial expression described below. This is then defined as the boundary for the Gradation and Indicatrix groups.

**Third polynomial expression of the boundary**

i) The boundary curve of Indicatrix groups

$$Ees = a_1 h^3 + a_2 h^2 + a_3 h + b \qquad (7)$$

ii) The boundary curve of Gradation groups

$$Eeg = a'_1 h^3 + a'_2 h^2 + a'_3 h + b' \qquad (8)$$

The boundary curves of the Gradation and Indicatrix groups are shown in *figure 5*. The coefficients of the boundary curves are shown in *table 3*.

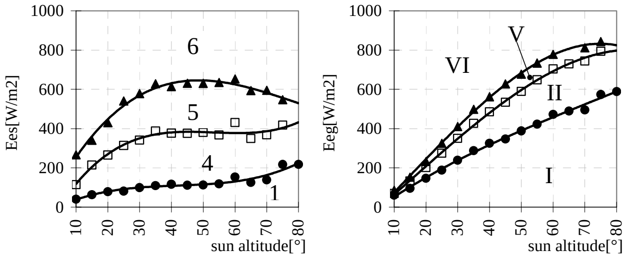



Figure 5 Bounding curves determined for the different Indicatrix and Gradation groups

Table 3 Coefficients of boundary curves

| | INDICATRIX | | | |
|---|---|---|---|---|
| | **a1** | **a2** | **a3** | **b** |
| **1 - 4** | 0.002 | -0.205 | 9.193 | -35.233 |
| **4 - 5** | 0.004 | -0.573 | 29.873 | -126.911 |
| **5 - 6** | 0.002 | -0.485 | 32.457 | -24.095 |

| | GRADATION | | | |
|---|---|---|---|---|
| | **a'1** | **a'2** | **a'3** | **b'** |
| **I - III** | 0.000 | -0.073 | 11.760 | -58.234 |
| **III - V** | -0.001 | 0.043 | 13.793 | -77.130 |
| **V - VI** | -0.002 | 0.064 | 16.138 | -91.317 |

## CALCULATION OF VERTICAL IRRADIANCE

In order to evaluate the methods of identifying sky type, we compared the vertical irradiance values determined from measured data of sky scanner, identified sky type, and uniform sky data. Calculations are described below.

**Calculation**

For identified sky type, applied formula (1) to the irradiance distribution, formula (9) is given. Given that the radiance measurement value of sky element NO.145 $r_{m,145}$ is the zenith radiance $r_z$, the relative radiance of sky element "*i*(=1, 2, ..., 144, 145)" of sky type "*j*(=1, 8, 13, 14, 15)" is determined from formula (10).

$$\frac{r_a}{r_z} = \frac{f(\chi)\varphi(Z)}{f(Z_s)\varphi(0)} \qquad (9)$$

$$r_{I,ij} = \frac{f_j(\chi_i)\varphi_j(Z_i)}{f_j(Z_s)\varphi_j(0)} r_{m,145} \qquad (10)$$

Next, the normal irradiance of each sky element is calculated. The view angle of the radiance sensor mounted on the sky scanner is 11°, and the solid angle of each sky element is given by formula (11).

$$\Omega = \pi[\sin(5.5° \times \frac{\pi}{180°})]^2 \qquad (11)$$

The ratio of the total solid angle of 145 measured sky elements and the solid angle of the whole sky is as follows:

$$\Omega \times 145 / 2\pi \simeq 0.67 \qquad (12)$$

Considering the ratio of the solid angle, the sky scanner measures approximately 2/3 of the area of the sky. Ineichen (Ineichen,P. et al., 1993.) reported that the sensitivity of the sky scanner-mounted luminance sensor (EKO MS300-LR, *figure6*, *7*, *table 4*) is 50% of the maximum value at a viewing angle 11°, and that the sensitivity decreases to 0% at a viewing angle of 18°. The sky scanner therefore measures more than 2/3 of the sky area. The specifications of the luminance sensor and radiance sensor of the EKO sky scanner are as described above. In this study however, the sky is divided into 145 sky elements without overlap or unassigned areas, and irradiance values are determined for each sky element. The celestial sphere is therefore divided into strips at each altitude band measured by the sky

Figure 6 Photograph of sky scanner EKO

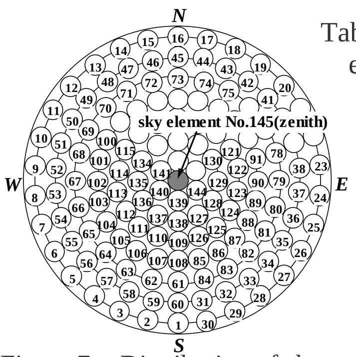



Figure 7 Distribution of sky elements

Table 4 Altitude and azimuth of sky elements

| Band of altitude | Sky element No. | Angle of elevation[°] | Azimuth step[°] |
|---|---|---|---|
| 1st | 1-30 | 6 | 12 |
| 2nd | 31-60 | 18 | 12 |
| 3rd | 61-84 | 30 | 15 |
| 4th | 85-108 | 42 | 15 |
| 5th | 109-126 | 54 | 20 |
| 6th | 127-138 | 66 | 30 |
| 7th | 139-144 | 78 | 60 |
| zenith | 145 | 90 | - |

scanner, and the surface areas of these strips $S_k$ are divided by the number of the sky elements $n_k$ within each band (*figure 8*; Nakayama, s., et al., 2002). The modified solid angle of the sky element $\omega_i$ are calculated below.

$$S_k = 2\pi(\cos z_{k+1} - \cos z_k) \quad (13)$$

$$\omega_i = \frac{S_k}{n_k} = \frac{2\pi(\cos z_{k+1} - \cos z_k)}{n_k} \quad (14)$$

The normal irradiance of the measured radiance distribution $R_{m,i}$ is calculated by using the modified solid angle of each sky element $\omega_i$. The values of horizontal sky radiation *Eed*, as measured by the pyranometer with shadow band, are used as reference values for comparison of the vertical irradiance values with each distribution. On this basis, the following adjustment of the direct solar radiation is performed. The width of the shadow band is equivalent to a viewing angle of 11.42°, and therefore the sky element that receives direct sunlight is considered the sky element that has a center of 11.42° angular distance from the sun. Therefore, the mean of the normal irradiance values of the circumjacent sky elements $R_{av}$ is assigned to the sky elements as the normal irradiance values $R_{m,i}$ (formulae (15), (16)).

$$R_{av} = \left(\sum \omega_i r_{m,i}\right) \Big/ n_{11.42} \cdots (5.71° < \chi_i < 11.42°) \quad (15)$$

$$R_{m,i} = \begin{cases} \omega_i r_{m,i} \cdots (\chi_i > 5.71°) \\ R_{av} \cdots (\chi_i \leq 5.71°) \end{cases} \quad (16)$$

In determining the irradiance of identified sky type $R_{I,ij}$, adjustment of the direct solar radiation isn't performed, and the irradiance $R_{I,ij}$ is calculated from the modified solid angle as described in formula (17).

$$R_{I,ij} = \omega_i r_{I,ij} \quad (17)$$

In order to compare the vertical irradiance value of each distribution, the total value of $R_{m,i}$, $R_{I,ij}$ is fitted to the reference value *Eed* (formulae (18), (19)).

$$\hat{R}_{m,i} = R_{m,i} \frac{E_{ed} + R_{av} n_{5.71}}{\sum_{i=1}^{145} R_{m,i} \sin h_i} \quad (18)$$

$$\hat{R}_{I,ij} = R_{I,ij} \frac{E_{ed} + R_{av} n_{5.71}}{\sum_{i=1}^{145} R_{I,ij} \sin h_i} \quad (19)$$

The vertical irradiance value of the measured radiance distribution $I_{m,sh}$ and that of identified sky type $I_{I,sh}$, are calculated from the normal irradiance of each sky element $\hat{R}_{m,i}$, $\hat{R}_{I,ij}$ (formulae (20), (21)).

$$I_{m,sh} = \sum_{i=1}^{145} \hat{R}_{m,i} \cos\theta_i \quad (20)$$

$$I_{I,sh} = \sum_{i=1}^{145} \hat{R}_{I,ij} \cos\theta_i \quad (21)$$

The vertical irradiance value of the uniform sky $I_{u,sh}$ is calculated as follows.

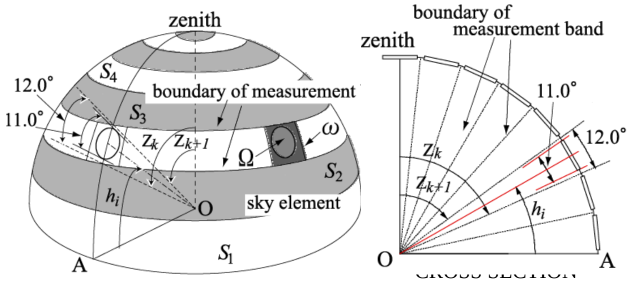



Figure 8 Divisions of the celestial sphere used to determine the modified solid angle of each sky element

$$I_{u,sh} = 0.5(E_{ed} + R_{av} n_{5.71}) \quad (22)$$

**Results**

*Figure 9* shows the monthly mean of the relative error between the vertical irradiance value determined from identified sky type, the value determined from uniform sky and the value determined from the most appropriate sky type from types 1,8,13,14 and 15. The vertical irradiance values were calculated in the four primary compass directions.

We now compare the relative error in each geographic direction.

**1) South**

Relative errors of uniform sky range from -20% in winter to +20% in summer, while the relative error of identified sky type is generally small but increases during winter to a value similar that of the uniform sky.

**2) West**

Relative errors of identified sky type range from -7% to ~ 6%, which is similar to values recorded in the southerly direction. Values of closest sky type are also small, and seasonal change is not evident. In contrast, the relative error of the uniform sky increases during summer to over 20%.

**3) North**

The relative error of uniform sky is 40% during winter and decreases to a minimum of 16% in summer. Error of the identified sky type is less than ±3% from April to October but increases during winter to a maximum of 13% in November. The error in identified sky type is small compared with that of uniform sky.

**4) East**

The relative error of the identified sky type is small, similar to that in the westerly direction, and with no discernable annual variation.

Though the relative errors to the north and south directions increase during winter, they are small compared to errors of the uniform sky.

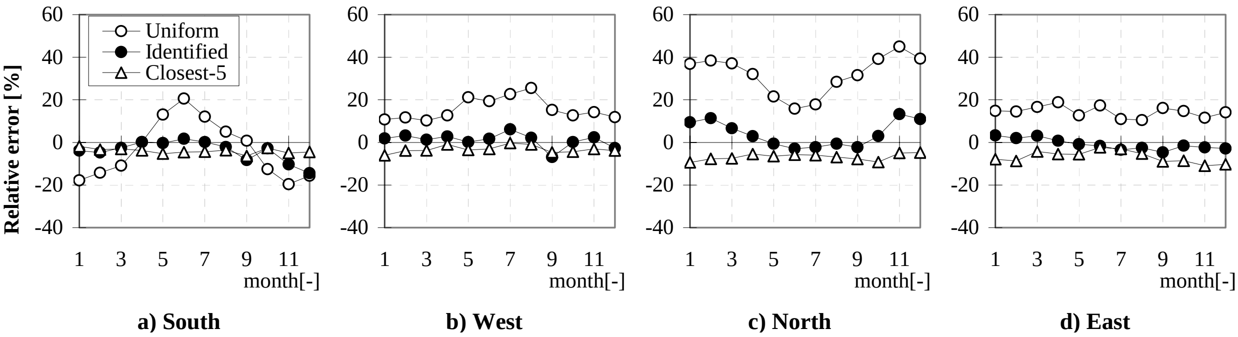



Figure 9 Monthly means of the relative error between measured vertical irradiance and estimates derived from identified sky type and uniform sky. Data is shown for four different geographic directions.
*The data labeled "Uniform" represents the relative error of uniform sky, while "Identified" represents that of identified sky type, and "Closest-5" represents that of the most appropriate sky type from types 1,8,13,14 and 15. The vertical irradiance values of "Closest-5" were calculated by the same procedure as that used for identified sky type.

## HEATING/COOLING LOAD

We now consider the heating/cooling load of a model room (*figure 10*). We calculated the heating/cooling loads of the measured radiance distribution, the uniform sky, and identified sky type in order to test the validity of the method outlined in this paper.

**Calculation**

The model room calculation is shown in *figure 10* and the calculation conditions are shown in *table 5*.
Based on this model room, the heating/cooling load was calculated for four different cases. In Model-S the window side of the room faces south, in model-W the window faces west, in model-N the window faces north, and in model-E the window faces east.
The vertical irradiance values calculated in section of calculation of vertical Irradiance are the values of sky radiation that intersect the outside of the wall.
We used a dynamic heating/cooling load calculation program to calculate the heating/cooling loads**.**
The calculation interval of the program is 1 hour. Consequently, we use hourly measurements of the moment values of sky radiation that intersect the outside of the wall during the heating/cooling load calculation.

**Results**

The monthly total values of heating/cooling load are shown in *figure 11*.
Values are similar between the different methods of calculating load (cf. *figure 9*), and the monthly total values of heating/cooling load of each sky radiance distribution record similar annual variation. The load of the measured radiance distribution is almost identical to that of identified sky type. We therefore consider it valid to use the values of solar radiation of identified sky type for calculating the heating/cooling load. There exist minor seasonal differences between the uniform sky load and the sky load. The summer uniform sky load is relatively large in model-S, model-W and model-N. This would result in larger calculated values of heating/cooling load than actual values (= measured radiance distribution).
The following sections compare values of heating/cooling load in each model.

**1) Model-S**

During winter (January ~ March), the values of heating/cooling load determined by measured radiance distribution are relatively low, while the values determined by uniform sky are the largest.
During summer (July ~ September), the values of load determined by uniform sky are greatest, while load determined by measured radiance distribution is similar to that of identified sky type.

**2) Model-W**

During August, the load determined from measured radiance distribution and identified sky type is about

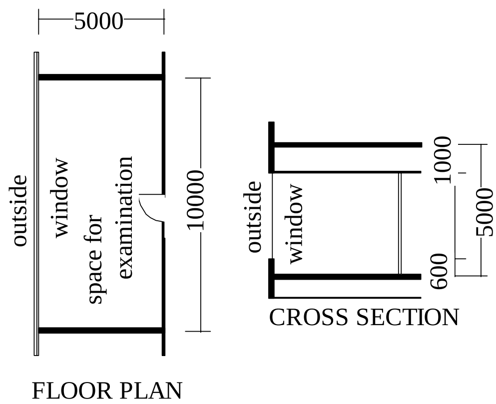
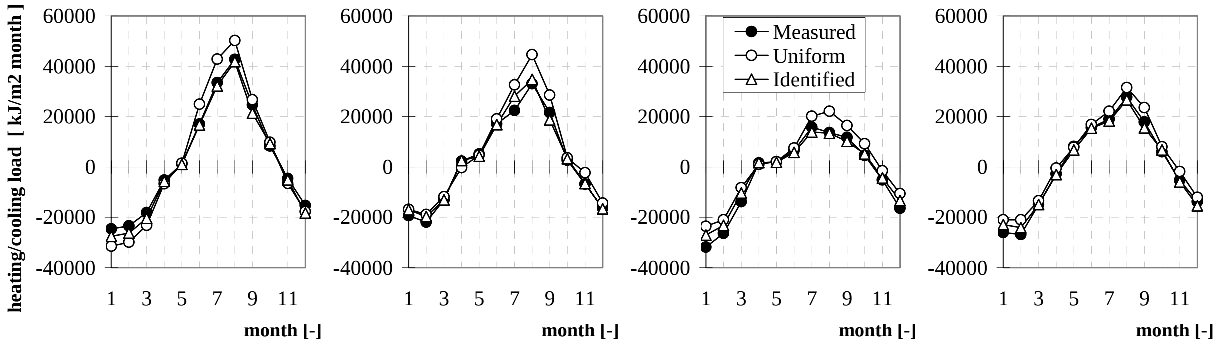



Figure 10 Plan of model room used for load calculations

Table 5 Conditions of heat/load calculations for model room

| Window glass | Ligtating | Person | Equipment | Outside air |
|---|---|---|---|---|
| **8** [mm] | **20** [W/m2] | **0.2** [W/m2] | **20** [W/m2] | **25** [m3/hour.person] |




**a) model-S** **b) model-W** **c) model-N** **d) model-E**

Figure 11 Comparison of the monthly estimates of heating and cooling load

75% of that determined by uniform sky.

**3) Model-N**

During summer, the loads calculated from uniform sky are larger than measured loads. The uniform sky load is up to 1.5 times greater than that estimated by identified sky type and measured sky. During winter, the radiance distribution load is greatest, which is in contrast to model-S winter readings.

**4) Model-E**

Differences between the loads predicted by the three models are minor, and winter patterns are similar to those of model-N.

## CONCLUSIONS

The boundary curves used to identify the sky type from *CIE standard general sky* were determined from the relationship between horizontal global sky radiation *Eeg* (mean of 15 minutes) and Gradation groups, the values of normal direct solar radiation *Ees* (mean of 15 minutes) and the Indicatrix groups. A method of identifying sky types 1,8,13,14,15 was developed from the boundary curves. The vertical irradiance value and heating/cooling load were calculated to test the validity of this method.

**values of vertical irradiance**

i) We calculated the relative error between the value of vertical irradiance value, measured from radiance distribution, and that determined using identified sky type. Comparison of the relative error of the vertical irradiance value by closest sky type, the uniform sky was performed.

ii) In comparison with closest sky type, relative errors didn't increase markedly. Even compared to uniform sky estimates, relative errors were small. Thus, it is possible to identify the sky type using the method proposed in this paper. This method enables more accurate predictions of solar radiation than values determined from uniform sky estimates.

**Heating/cooling load**

i) Differences such as those recorded in the relative error of vertical irradiance values are not evident in the heating/cooling data. The monthly total values of heating/cooling load of each sky radiance distribution are similar in every case, as are the patterns of annual change.

ii) The load calculated from measured radiance distribution is similar to estimates derived from the identified sky type. It is therefore valid to calculate the heating/cooling load using solar radiation values derived from identified sky type.

iii) In some cases, the differences in load estimated from uniform sky and identified sky type vary between summer and winter. The summer load values derived from the uniform sky model are especially large for model-S, model-W and model-N. There exists a tendency to overestimate values of heating/cooling load.

**Nomenclature**

$L_a$ : luminance of a sky element [$\mathrm{cd/m^2}$]

$L_z$ : zenith luminance [$\mathrm{cd/m^2}$]

$\chi$ : shortest angular distance between a sky element and the sun [rad]

$\chi_i$ : shortest angular distance between a sky element *i* of sky scanner and the sun [rad]

$Z_i$ :angular distance between a sky element *i* of sky scanner and the zenith [rad]

$h_i$ : altitude of a sky element *i* of sky scanner [rad]

$Z$ : angular distance between a sky element and the zenith [rad]

$Z_s$ : angular distance between the sun and zenith [rad]

$z_k$ : angular distance between the boundary between *k*th altitude band and *k+1*th altitude band of sky scanner and the zenith ( $z_1 = \pi/2$ , $z_{8+1} = 0$ ) [rad]

$a, b$ : gradation parameter [-]

$c, d, e$ : scattering indicatrix parameter [-]

$\alpha$ : azimuth of a sky element [rad]

$\alpha_s$ : azimuth of the sun [rad]

$r_a$ : radiance of a sky element [$\mathrm{W/m^2 \cdot sr}$]

$r_z$ : radiance of the zenith [$\mathrm{W/m^2 \cdot sr}$]

$r_{I,ij}$ : radiance of sky element *i* of identified sky type *j* [$\mathrm{W/m^2 \cdot sr}$]

$r_{m,i}$ : radiance of sky element *i* of sky scanner [$\mathrm{W/m^2 \cdot sr}$]

$S_k$ : surface area of *k*th altitude band of sky scanner [-]

$\Omega$ : solid angle of a sky element [sr]

$\omega_i$ : modified solid angle of sky element *I* [sr]

$r_{m,145}$ : measured radiance of sky element No.145 $[\mathrm{W/m^2 \cdot sr}]$
$R_{m,i}$ : irradiance of sky element *i* of sky scanner $[\mathrm{W/m^2}]$
$R_{I,ij}$ : irradiance of sky element *i* of identified sky type $[\mathrm{W/m^2}]$
$R_{av}$ : means of irradiances of sky elements ( $5.71 < \chi_i < 11.42$ ) $[\mathrm{W/m^2}]$
$\theta_i$ : angle of incidence to the vertical plane [rad]
$\hat{R}_{m,i}$ : irradiance of sky element *i* of sky scanner fitted to *Eed* $[\mathrm{W/m^2}]$
$\hat{R}_{I,ij}$ : irradiance of sky element *i* of identified sky type *j* fitted to *Eed* $[\mathrm{W/m^2}]$
$I_{m,sh}$ : vertical irradiance of sky scanner $[\mathrm{W/m^2}]$
$I_{I,sh}$ : vertical irradiance of identified sky type $[\mathrm{W/m^2}]$
$I_{u,sh}$ : vertical irradiance of uniform sky $[\mathrm{W/m^2}]$
$E_{eg}$ : horizontal global sky radiation $[\mathrm{W/m^2}]$
$E_{ed}$ : horizontal sky radiation $[\mathrm{W/m^2}]$
$E_{es}$ : normal direct solar radiation $[\mathrm{W/m^2}]$
$n_k$ : the number of sky elements in *k*th altitude band [-]
$n_{11.42}$ : the number of sky elements ( $5.71 < \chi_i < 11.42$ ) [-]
$n_{5.71}$ : the number of sky elements ( $\chi_i \le 5.71$ ) [-]

**Index**

*i* : number of sky element(=1~145)
*j* : number of sky type(=1, 8, 13, 14, 15)
*k* : number of altitude band of sky scanner(=1~8)
*m* : Sky Scanner
*I* : identified sky type
*u* : uniform sky

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Table 6 Parameters of sky types of the *CIE Standard general sky*

| Sky type | Gradation group | Indicatrix group | a | b | c | d | e | Description of liminance distribution |
|---|---|---|---|---|---|---|---|---|
| 1 | I | 1 | 4.0 | -0.7 | 0 | -1.0 | 0 | **CIE Standard Overcast Sky**, Steep luminannce gradation towards zenith,azimuthal |
| 2 | I | 2 | 4.0 | -0.7 | 2 | -1.5 | 0.2 | Overcast, with steep luminannce gradation and slight brightening towards the sun |
| 3 | II | 1 | 1.1 | -0.8 | 0 | -1.0 | 0 | Overcast, with moderately graded with azimuthal uniformity |
| 4 | II | 2 | 1.1 | -0.8 | 2 | -1.5 | 0.2 | Overcast, with moderately graded and slight brightening towards the sun |
| 5 | III | 1 | 0.0 | -1.0 | 0 | -1.0 | 0 | **Sky of uniform luminance** |
| 6 | III | 2 | 0.0 | -1.0 | 2 | -1.5 | 0.2 | Partly cloudy sky, no gradation towards zenith, slight brightening towards the sun |
| 7 | III | 3 | 0.0 | -1.0 | 5 | -2.5 | 0.30 | Partly cloudy sky, no gradation towards zenith, brighter circumsolar region |
| 8 | III | 4 | 0.0 | -1.0 | 10 | -3.0 | 0.5 | Partly cloudy sky, no gradation towards zenith, distinct solar corona |
| 9 | IV | 2 | -1.0 | -0.6 | 2 | -1.5 | 0.2 | Partly cloudy sky, with the obscured sun |
| 10 | IV | 3 | -1.0 | -0.6 | 5 | -2.5 | 0.30 | Partly cloudy sky, with brighter circumsolar region |
| 11 | IV | 4 | -1.0 | -0.6 | 10 | -3.0 | 0.5 | White-blue sky with distinct solar corona |
| 12 | V | 4 | -1.0 | -0.3 | 10 | -3.0 | 0.5 | **CIE Standard Clear Sky ,low luminance turbidity** |
| 13 | V | 5 | -1.0 | -0.3 | 16 | -3.0 | 0.30 | **CIE Standard Clear Sky ,polluted atmosphere** |
| 14 | VI | 5 | -1.0 | -0.2 | 16 | -3.0 | 0.30 | Cloudless turbid sky with broad solar corona |
| 15 | VI | 6 | -1.0 | -0.2 | 24 | -2.8 | 0.2 | White-blue turbid sky with broad solar corona |