Paper

Classification of Sky Conditions by the Ranges of Insolation Indices Considering CIE Standard for General Sky

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ABSTRACT

This study introduces a method to classify sky conditions from overcast to clear by the values of insolation indices. Number of sky types and combination of insolation indices to classify sky types were investigated. Fifteen groups were clustered regarding nine indices by nearest centroid sorting method. Then groups were put together into sky conditions by considering the frequency distributions of CIE general sky types for each group and the frequency distribution of groups for each luminance distribution type. Seven sky conditions were found as a result. Indices to discriminate next sky conditions were found and then the most appropriate combination for total discrimination was decided : turbidity, clearness index, brightness and normalized global illuminance. Sky condition discrimination tree on the basis of the value of the indices was formed by a yearly data of International Daylight Measurement Program at Kyoto station and verified by the data of another year. By this method, illuminance and irradiance measurements can be separated into seven sky conditions considering CIE general sky types by the ranges of four indices without sky luminance distribution measurements.

KEYWORDS: CIE General Sky, insolation indices, International Daylight Measuring Program, sky luminance distribution

1. Introduction

CIE Standard for General Sky was standardized in 2003 as fifteen standard relative luminance distribution types which are based on six groups of luminance gradation function and six groups of scattering indicatrix function[1]. The ratio of the luminance of an arbitrary sky element to the zenith luminance is expressed as multiple of the gradation function by the indicatrix function, adopting the idea of a CIE clear sky model that incorporates a physical theory of scattering of sunlight. Further utilization of day lighting is expected by using this detailed sky luminance distribution model.

The General Sky type of a certain sky can be estimated if its luminance distribution is known. However, it is not easy to predict the sky type merely using generally available data of irradiance and illuminance, even though the approximate ranges of sky indices are shown in former studies.

Methods to classify the measured data into sky types using a combination of insolation indices have been examined. Perez et al. proposed All-Weather sky luminance distribution model which parameters are sky clearness and brightness[2]. Igawa et al. proposed All Sky Model that uses standard global illuminance as an index to represent sky luminance distribution from clear sky to overcast sky continuously[3]. Igawa et al. also examined cloud ratio, permeability, turbidity, brightness and clearness. Kittler et al. showed the usual ranges of the turbidity and the sky brightness and frequent range of the normalized diffuse illuminance, and probable range of the ratio of zenith luminance to the diffuse illuminance. Inanuma et al. made standard weather data including sky luminance distribution by using cloud ratio as a simple index of the weather[4]. Nakamura et al. represented the frequent distribution of clear sky, intermediate sky, and overcast sky by combination of the cloud cover and sunshine duration[5].

This study introduces appropriate classification of insolation conditions by indices to classify the sky types used in the former studies considering the CIE General Sky model of luminance distribution. On the basis of the illuminance, irradiance and sky luminance distribution measured at Kyoto research class station of International Daylight Measurement Program, the optimum combinations of the indices to classify sky types are clarified by analyzing the relationships between the ranges of the indices and the General sky types. Then a discrimination tree to specify the sky type for a given irradiance and illuminance is proposed by necessary and sufficient combination of the insolation indices when the luminance distribution is unknown.

2. Measurement

Sky luminance distribution, irradiance and illuminance were measured at Kyoto research class station of International Daylight Measurement Program (35.03 N, 135.79 E and 90 m above sea level). Figure 1 shows the view of the setting of the measurement instruments for illuminance and irradiance. Figure 2 shows the view of the sky scanner (EKO ML-010SZ) on site. Figure 3 shows the altitude and azimuth of measured sky elements for luminance. It costs about three min to measure the 145 sky elements.

Kyoto station started the measurement of illuminance and irradiance at April 1991 and started the measurement of sky luminance distribution at June 1992. These measurements are continued until June 2000, but the duration when both data were recorded continually for more than a year is only about three years. Data from July 1998 to June 1999 were used in this study. Illuminance and irradiance were recorded every minute and luminance was recorded every fifteen minutes. 15,557 set of illuminance, irradiance and luminance distribution data of every fifteen minutes were acquired for solar altitude above five degree.

Shadow bands of the width of 5.0 cm and the radius of 25.0 cm were used to screen the direct solar illuminance and irradiance to measure the diffuse irradiance and illuminance. The rings were reset every three or four days by sighting devices and sunlight in conformity with the changing values of the declination of the sun. The underestimated diffuse components were corrected by the equation of Drummond[6].

After the correction of the diffuse component, CIE data quality control test for illuminance and irradiance[7] was applied to eliminate inappropriate automatically acquired data. Passing rates of the consistent test (test 2 in equations (1) for the tolerance ranges of 25 %) among global, diffuse and direct components are lower, 94.6 % for irradiance and 82.8 % for illuminance, where almost of the other rates are more than 99 % except for that for luminance efficacy of direct component, 71.0 %.

test2.1: $E_{eg} = (E_{es} \cos\theta_z + E_{ed}) \pm 25\%$ ……… (1)

test2.2: $E_{vg} = (E_{vs} \cos\theta_z + E_{vd}) \pm 25\%$

Figure 1 Settings of measuring instruments

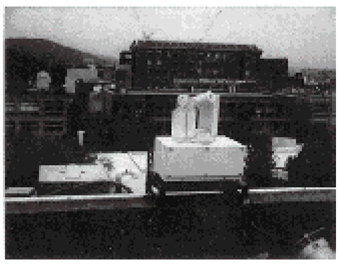

Figure 2 Sky scanner on site

10.005 sets of data were passed the tests for the tolerance ranges of 25 % and used in this study.

3. Estimation of CIE General sky types

The CIE general sky types of given skies were identified by comparing D_k, sum of the root mean square error in equations (2), between model relative luminance of the sky element i in model k m_{ki}, and the measured relative luminance to the zenith luminance r_i, among 15 models of CIE General sky. The type k of the least D_k value is specified as the sky type of the given luminance distribution measurement.

$$D_k = \sum_{i=1}^{145} (r_i - m_{ki})^2$$

$$m_{ki} = \frac{f_k(\chi_i)\cdot\varphi_k(Z_i)}{f_k(Z_s)\cdot\varphi(0)}$$

$$\varphi_k(Z_i) = 1 + a_k \exp\left(\frac{b_k}{\cos Z_i}\right)$$

$$f_k(\chi_i) = 1 + \left[c_k \exp(d_k\chi_i) - \exp\left(d_k\frac{\pi}{2}\right)\right] + e_k \cos^2\chi_i$$

$$(k = 1 \text{ to } 15, \quad i = 1 \text{ to } 145) \quad \ldots\ldots\ldots\ldots(2)$$

,where f_k is a scattering indicatrix function of the model k, χ_i is the angular distance between the element i and the sun, ϕ_k is a luminance gradation function of the model k, and Z_i is the zenith angle of the element i. a_k, b_k, c_k, d_k and e_k are the parameters for model k.

Figure 4 shows the examples of the contour lines of the relative luminous distribution for the measurements and the identified models. It seemed that the identifications are proper for these insolation conditions and solar heights, although the measurements are partly not uniform.

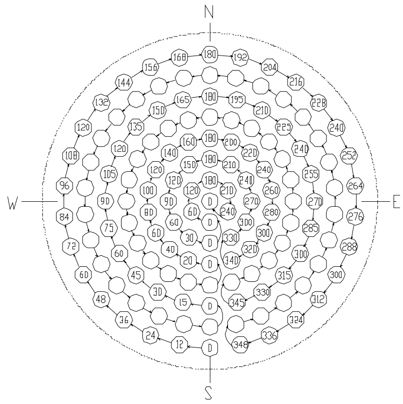

Figure 3 Measurement points of sky luminance distribution

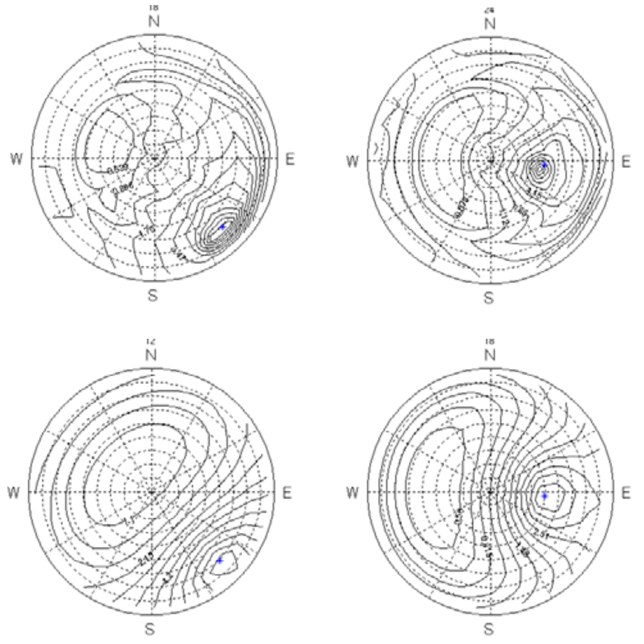

Figure 4　Examples of the relative luminous distribution
(Upper : measured　Lower : estimated model)
(Left : : type 11　Right : : type 13)

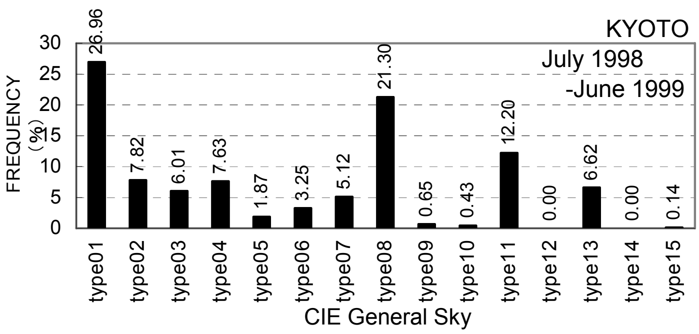

Figure 5　Frequency distribution of sky types

Figure 5 shows the frequency distribution of the estimated CIE General Sky types. Type 1, standard overcast sky, is the most frequent (27.0 %). The second is type 8 (21.3 %), partly cloudy with no gradation towards zenith and with distinct solar corona. The third is type 11 (12.2 %), white-blue sky with distinct solar corona and the forth is type 13 (6.6 %), CIE standard clear sky with polluted atmosphere. Type 9, 10, 12 (CIE clear sky with low turbidity), 14 and 15 seldom appeared. Tregenza noted that type 1, 3, 8 and 13 are recognized for Garston, type 1, 3, 8 and 13 for Singapore, type 1, 4, 8 and 13, for Sheffield are recognized[8]. Number of the typical skies is common for this study in Kyoto.

Based on the above result, fifteen types were classified into six larger Types as following in this study: Type 1 of the overcast sky, Type 1-d of the cloudy types other than Type 1, Type 8 of the intermediate sky, Type 8-d of the intermediate types other than Type 8, Type 11 and 12, Type 13 and 14 and 15.

4. Clustering groups by insolation indices

Nine indices were examined: cloud ratio, permeability, turbidity of daylight, clearness, brightness, normalized sky illuminance, normalized global illuminance, the ratio of zenith luminance to sky illuminance[9], and normalized direct illuminance. They have been used in former studies to classify sky luminance distributions or insolation conditions. The abbreviations and equations of the indices are shown in Figure 6. Sunlight constant E_{v0} is 133.8 klx,

Cloud ratio: $CLDV = \dfrac{E_{vd}}{E_{vg}}$

Permeability: $PERV = \sqrt[m]{\dfrac{E_{vs}}{E_{vo}}}$

Turbidity: $TURV = \dfrac{1+0{,}0045m}{0.1m} \cdot \ln\dfrac{E_{vo}}{E_{vs}}$

Clearness: $CLER = \dfrac{(E_{ed} + E_{es}) / E_{ed} + 1{,}041\gamma_s^{\,3}}{1+1{,}041\gamma_s^{\,3}}$

Brightness: $BRGT = m\dfrac{E_{ed}}{E_{eo}}$

Normalized diffuse illuminance:

$EVDM = m\dfrac{E_{vd}}{E_{vo}}$

Normalized global illuminance:

$EVGM = m\dfrac{E_{vg}}{E_{vo}}$

Ratio of zenith luminance to sky illuminance:

$LERT = \dfrac{L_z}{E_{vd}}$

Normalized direct illuminance:

$EVSM = m\dfrac{E_{vs}}{E_{vo}}$

Figure 6　Abbreviations and equations of the indices

and solar constant E_{e0} is 1,354 W/m^2. Equation by Kasten and Young[10] was used for relative optical air mass m as follows.

$$m = \frac{1}{\sin\gamma_s + 0.50572(\gamma_s + 6.07995)^{-1.6364}} \qquad \text{………..(3)}$$

If more than one value of the indices were apart from the average over two times of the standard deviation, the data were omitted. The rest 7,621 data were clustered into 15 groups related to the values of nine indices using the nearest centroid sorting method. Two general methods to

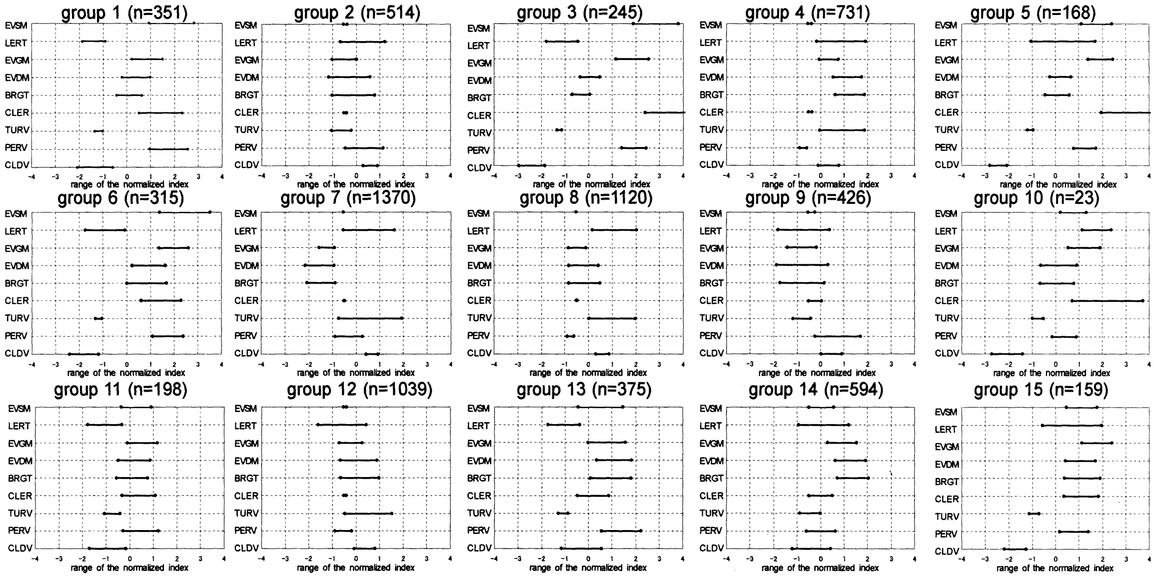

Figure 7　Ranges of the indices for clustered groups (90 percentile)

form clusters exist: one specifies numbers of the clusters; another specifies the limits of the distance among clusters. This study used the former. The specified number of clusters was fifteen regarding the number of sky types in the CIE general sky model. Several grouping methods were examined; the method used herein was inferred to be appropriate. The ranges of nine indices and the number of the clustered data of the Groups are shown in Figure 7.

5. Discrimination of Seven Peculiar sky Conditions

Then fifteen Groups were put together into peculiar sky conditions from overcast to clear considering both the frequency distribution of the larger sky Types for each Group and the frequency distribution of Groups for each Type. As a result, fifteen Groups were integrated into seven peculiar insolation conditions. They were ranked from overcast to clear according to the ranges of the values of indices.

Best combinations of indices were sought to estimate Conditions for given measurements of irradiance and illuminance, without measurements of sky luminance distribution. Ranges of the nine indices for seven Conditions were calculated. Table 1 shows the ranges of the indices for seven sky types (mean ± s.d.). Indices that were effective to discriminate neighbor Conditions in the rank from overcast to clear were determined first. Then the necessary and sufficient combination of indices for total discrimination was decided. Combination of four indices was chosen as a result: turbidity, clearness, brightness, and normalized global illuminance. The necessary measurement items are sky irradiance, global irradiance, and global and direct illuminance. Figure 4 shows the ranges of four indices for seven sky conditions.

A discrimination tree for Conditions was formed based on the ranges of the indices as shown in Figure 5. Conditions can be discriminated according to the values of turbidity, clearness, brightness and normalized global illuminance of the given data using the tree. Other yearly data of IDMP stations were used to verify the tree. Irradiance and illuminance data were put into the tree and classified into seven Conditions according to the values of four indices as shown in Figure 6. A frequency distribution of CIE General Sky Types was inspected for each Group. The distributions of the Types resembles that of the data used to form the tree, especially for Conditions of cloudy side,

Table 1　Ranges of the indices for seven sky types (means ± s.d.×1.1)

Sky type	TURV	CLER	BRGT	EVGM
Overcast sky	27.663-58.079	0.993-1.070	0.073-0.206	0.111-0.298
Semi-overcasr sky	24.490-50.105	0.935-1.046	0.206-0.314	0.303-0.461
Cloudy sky	8.782-19.801	0.962-1.067	0.127-0.235	0.183-0.342
Intermediate sky	7.424-21.186	0.649-0.947	0.259-0.347	0.451-0.693
Cloud clear sky	9.597-17.879	0.636-0.837	0.188-0.258	0.393-0.563
Semi-clear sky	4.549-8.436	0.497-0.708	0.195-0.282	0.533-0.805
Clear sky	4.807-9.143	0.374-0.500	0.168-0.224	0.684-0.842

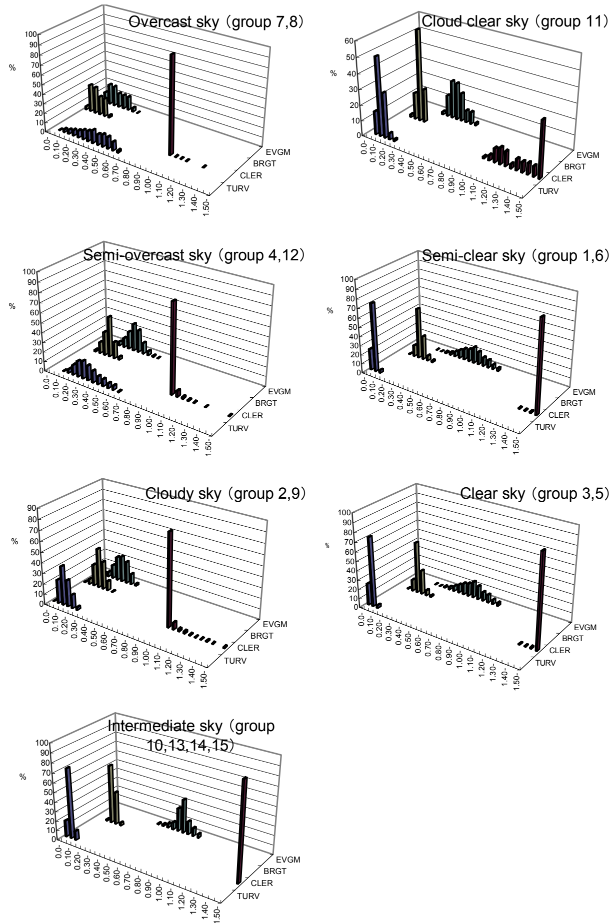

Figure 8 Frequency distributions of four indices (full range)

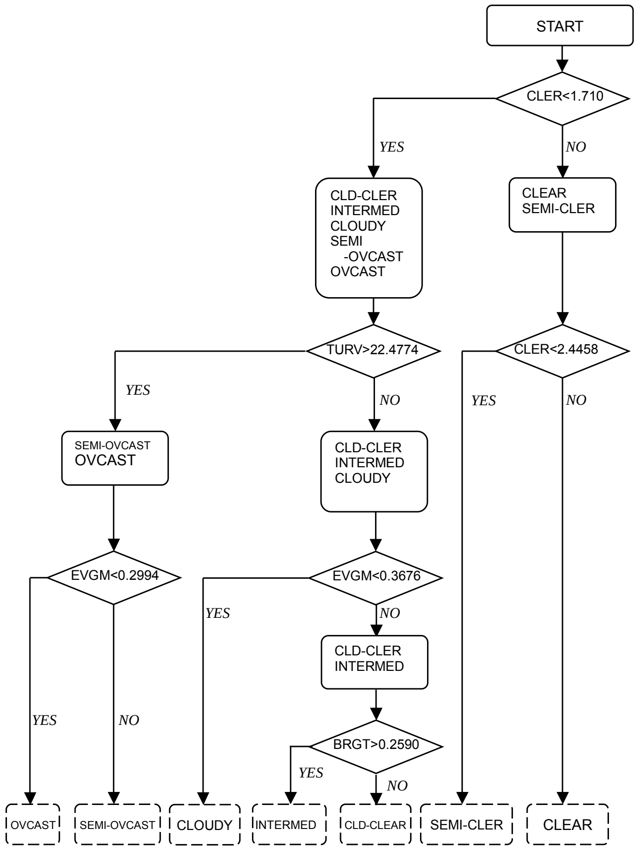

Figure 9 Discrimination tree

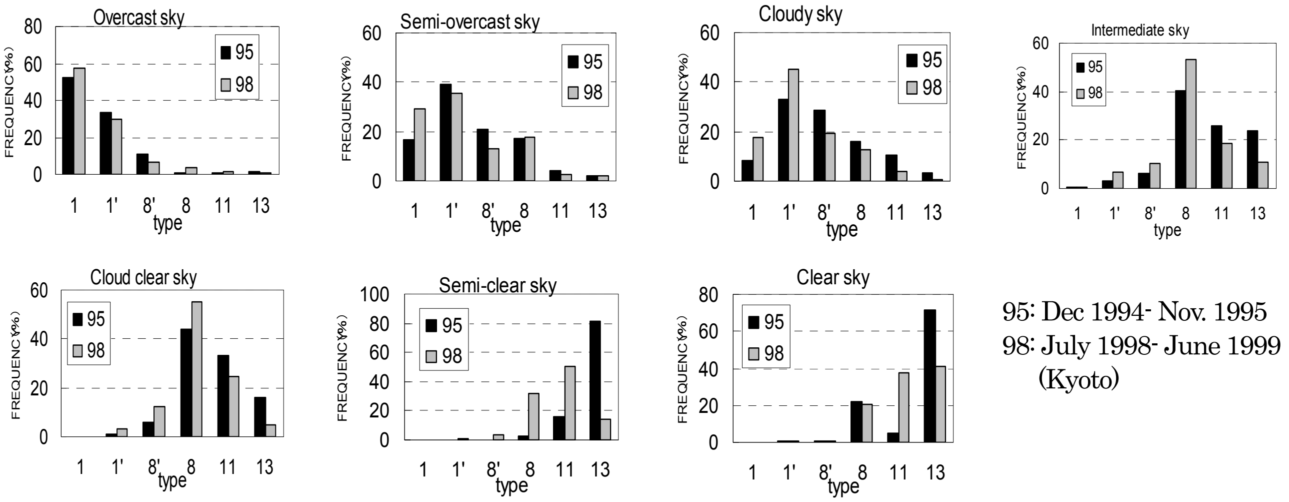

Figure 10 Comparison of the frequency distributions of general sky types between original data to form the tree (98) and another yearly data discriminated by the tree (95)

although the frequency of type-13 was different.

6. Concluding remark

A method to form a discrimination tree of sky conditions by using only illuminance and irradiance data was introduced in this study. Sky condition from overcast to clear of the measured set of illuminance and irradiance can be estimated by the method without measurement of sky luminance distribution. The peculiar sky conditions might differ according to the measurement sites. Further studies are needed to form more generally recognized sky conditions and discrimination tree by using data from other measurement sites.

References

(1) CIE: Spatial Distribution of Daylight, CIE Standard General Sky, CIE Standard 011-2003, (2003).

(2) Perez, R., Seals, S. and Michalsky, J.: All-weather model for sky luminance distribution - Preliminary configuration and validation, Solar Energy, 50 (3), pp.235-245, (1993).

(3) Igawa, N., Nakamura, H., Matsuzawa, T. and Koga, Y.: All sky model as a standard sky luminance distribution, J. Illum. Engng. Inst. Jpn., Vol.85 (2), pp.131-140, (2001).

(4) Inanuma, M., Yoshimura, T., Takeda, H. and Asada, H.: An experimental study of the development of standardized annual weather data with sky luminance distribution based on long-term observation data, J. Environ. Eng., AIJ, No.576, pp.43-48, (2004).

(5) Nakamura, H., Oki, H. and Hayashi, Y.: A study on the estimation of the relative frequency of occurrences of the Clear Sky, the Intermediate Sky and the Overcast Sky in Japan, J. Light. Vis. Env., 9 (2), pp.76-85, (1985).

(6) Drummond, A. J.: On the measurement of sky radiation, Archive. Met. Geophys. Biakl. Serie B., Vol.9, pp.413-436, (1956).

(7) CIE: Guide to recommended practice of daylight measurement, Part C, Data quality control, Processing and dissemination, Publication CIE, 108-1994, (1994).

(8) Tregenza, P. I.: Standard skies for maritime climates, Lighting Research and technology, 31(3), pp.97-106, (1999).

(9) Kittler, R., Darula, S. and Perez, R.: A set of standard skies - Characterizing daylight conditions for computer and energy conscious design, Albany Atmospheric Sciences Research Center, State University of New York, (1998).

(10) Kasten, F. and Young, A.: Revised optical air mass tables and approximation formula, Applied Optics, Vol.28, pp.4735-4738, (1989).

Nomenclature

E_{eg}	:Global irradiance	E_{e0}	:Solar constant
E_{ed}	:Diffuse irradiance	E_{v0}	:Sunlight constant
E_{es}	:Direct irradiance	L_z	:Zenith luminance
E_{vg}	:Global illuminance	γ	:Solar altitude
E_{vd}	:Diffuse illuminance	γ_s	:Zenith angle
E_{vs}	:Direct illuminance	m	:Optical air mass