COMPARATIVE STUDY OF SKY LUMINANCE MODELS IN THE TROPICAL CONTEXT

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ABSTRACT

Reliable sky luminance models are considered to be *conditio sine qua non* for accurate computational simulation of daylight distribution in architectural spaces. Toward this end, the paper compares six sky models specifically with regard to their applicability in the tropical context.

INTRODUCTION

Reliable prediction of illuminance and luminance distribution in daylit interiors necessitates an accurate model of the daylighting source, i.e., the sky. Until recently, most lighting simulation programs used only simplified sky luminance models, such as standardized clear, overcast or even uniform skies. There have been concerns that the results obtained from such programs may not reflect intermediate conditions between the two extremes of completely clear or completely overcast. In the case of the uniform sky model the location and time are not even considered. In recent years, a number of more elaborate sky luminance models have been developed. This paper presents a preliminary comparative assessment of six such models and the CIE standard overcast sky with regard to their applicability in the tropical context, using measured data in Singapore.

THE SKY MODELS

The six sky luminance distribution models considered are:

1) CIE standard overcast sky: This sky as defined by the CIE has a non-uniform, isotropic luminance distribution, increasing from the horizon to the zenith (Hopkinson et al. 1966).

2) All weather sky model: Developed by Perez et al. (1993) on the basis of sky luminance data collected for predominantly clear skies, this model uses a clearness index and a sky brightness factor to compute the sky luminance distribution.

3) ASRC-CIE model: This model is a linear combination of four skies - the CIE or Kittler clear sky, the Gusev turbid clear sky, the intermediate sky and the CIE overcast sky. The coefficients of linear combination are computed using the sky clearness and the sky brightness factors (Littlefair 1994).

4) Brunger's model: This model describes the sky luminance distribution by parameterizing insolation conditions as functions of the ratio of global to extraterrestrial irradiance (Brunger 1987).

5) Kittler's model: Sky luminance distribution is described by parameterizing the insolation conditions in terms of the illuminance turbidity which is given as a function of direct normal extraterrestrial illuminance and direct normal ground illuminance (Kittler 1986).

6) Perraudeau's model: A theoretical formulation of a cloud ratio is used for computing sky luminance distribution (Perraudeau 1988).

The above models (with the exception of the CIE standard overcast sky) base their sky luminance distribution computations on the basic parameters of solar altitude, solar azimuth, diffuse horizontal irradiance, global or direct normal irradiance, and extraterrestrial solar irradiance. Kittler's model needs the ground reflectance as well.

For the purpose of the present study, the solar altitude, azimuth, and extraterrestrial solar irradiance are computed using Sol-Aris (Mahdavi and Lam 1994, Mahdavi et al. 1994). Values of diffuse horizontal irradiance and global irradiance are obtained through measurement (see next section). The direct normal irradiance is computed using the diffuse and global irradiance values and the solar altitude.

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MEASUREMENT

Measurement Setup

The Daylight Measurement Station at the National University of Singapore was upgraded from a General Class Station to a Research Class Station with the installation of a sky scanner in June 1996. The sky luminance distribution measurements are augmented by diffuse and global irradiance and illuminance measurements which are being used to validate the sky luminance distribution models.

The sensors for the measurement of the illuminances and irradiances are placed on the roof of the lift shaft of a four storey building sited on the top of a ridge to maximize unobstructed views of the sky. The following measurements are taken and data stored on an hourly basis from 7 a.m. to 7 p.m. daily.

(a) Global irradiance on the horizontal and on the north, east, south and west facing vertical surfaces.
(b) Diffuse irradiance on the horizontal.
(c) Global illuminance on the horizontal and on the north, east, south and west facing vertical surfaces.
(d) Diffuse illuminance on the horizontal.

The maximum, minimum, average and instantaneous hourly values are stored.

Shadow rings are used to provide the diffuse horizontal illumination and radiation values. The sensors for measuring illuminance and irradiance on vertical surfaces are screened from ground reflections by a circular ring and four diagonal fins within the circular area, painted matt black.

The sky scanner is installed on the roof of a lift shaft in the same building complex where the above equipment is placed. It is connected to a data logger placed in a nearby room. It measures both luminance and radiance at 145 points of the sky by scanning the sky dome. Scans are taken every half hour. The measurement points are shown in Figure 1.

Data Collection Period

Data collected for 41 days during the months of June, July, September, and November 1996, were used for the study presented. Based on considerations pertaining to data quality, the measurement results are organized in terms of two databases: a "high-quality" database and a "medium-quality" database. The high-quality database does not include the luminance values of patches with an altitude of less than 10 degrees. Likewise, the luminance values of the patches with an angular distance of less than 10 degrees to the sun are not included. In this paper, we refer to this set of the collected data as the "reduced database". The medium-quality database contains the entire collected data and will be refered to as the "original database". While, we compare the model predictions with the reduced database in the following section, comparative references to the original database are made in the discussion section.

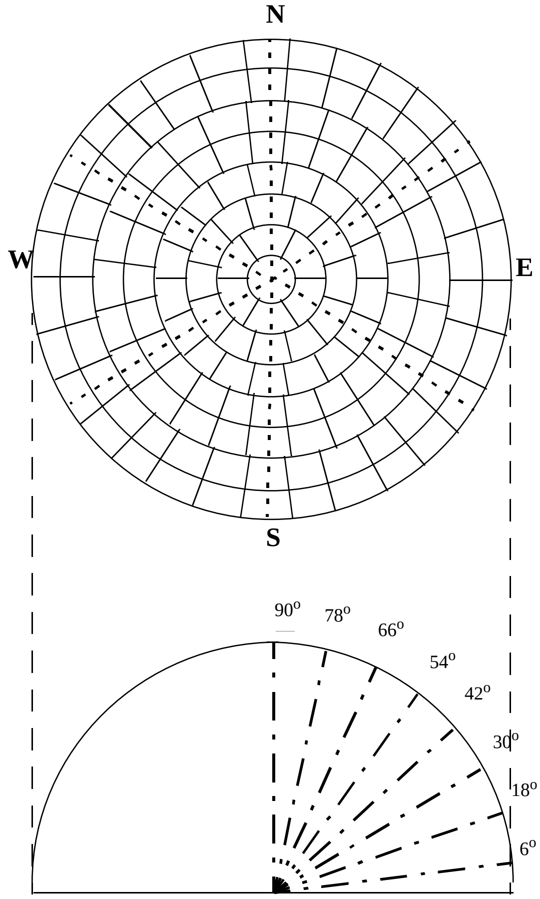

Figure 1: The measurement points for the sky scanner.

RESULTS

Comparison Based on Correlation

A total of about 45000 pairs of measured-predicted luminance values (reduced database) were used to determine the degree of correlation (r) between the measurements and the predictions derived for each model. The results are summarized in Table 1.

Table 1: Correlation Between Measured and Predicted Values (Reduced Database)

Model	*correlation (r)*
Perraudeau	0.87
Kittler	0.84
Perez	0.83
Brunger	0.81
ASRC-CIE	0.77
CIE	0.65

Comparison Based on Relative Error

To obtain an intuitive sense of the deviations between measurements and predictions, a mean relative error is formulated according to the following definition

$$RE_m = \left[\exp\left(\frac{1}{n} \sum_{i=1}^{n} \ln \frac{L_{p,i}}{L_{m,i}} \right) - 1 \right] 100 \qquad [\%]$$

where
$L_{m,i}$ is the measured sky patch luminance
$L_{p,i}$ is the predicted sky patch luminance

For n = 1, this formulation obviously yields the "classical" definition of relative error (RE):

$$RE = \frac{L_p - L_m}{L_m} 100 \qquad [\%]$$

The results are given in Table 2. Figure 2 shows the mean relative errors with a deviation range which contains 70% of all relative error values.

Table 2: Mean Relative Errors of the Predicted Values (Reduced Database)

Model	*Mean Relative Error* [%]
Brunger	-0.3
ASRC-CIE	-15.9
Perraudeau	21.1
Perez	24.4
Kittler	26.8
CIE	28.6

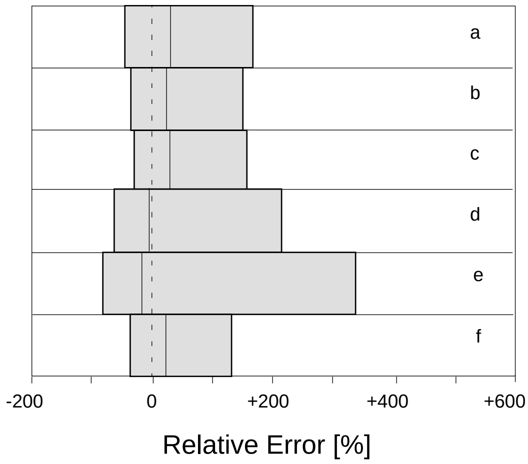

Figure 2: Mean Relative Errors with the corresponding Deviation Ranges containing 70% of the relative errors. (a: CIE, b: Perez, c: Kittler, d: Brunger, e: ASRC-CIE, f: Perraudeau) (Reduced database)

Figure 3 shows the mean relative errors of the models as a function of the sun position (expressed as the angular distance of the relevant sky patch from the sun position).

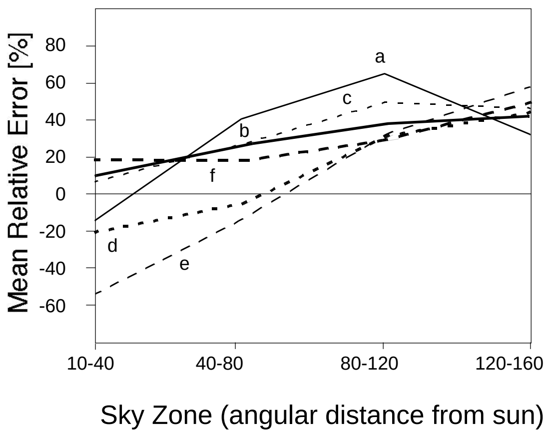

Figure 3: Mean relative error as a function of the angular distance of the relevant sky patch from the sun. (a: CIE, b: Perez, c: Kittler, d: Brunger, e: ASRC-CIE, f: Perraudeau)

Comparison Based on Linear Regression

The following diagram (Figure 4) shows the measurement vs. prediction regression lines for all models.

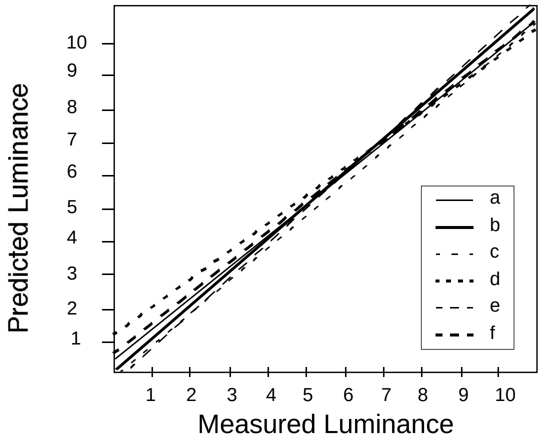

Figure 4: Measurement vs. Prediction regression lines for the six sky models. (a: CIE, b: Perez, c: Kittler, d: Brunger, e: ASRC-CIE, f: Perraudeau) (Reduced database)

Daily Patterns

Figures 5, 6 and 7 illustrate for three "typical" days the daily pattern of relative errors.

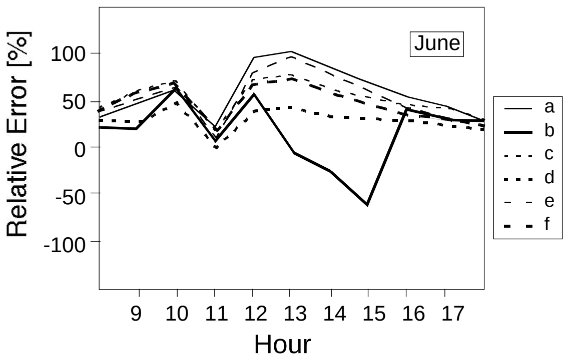

Figure 5. Relative errors for a "typical" day in June. (a: CIE, b: Perez, c: Kittler, d: Brunger, e: ASRC-CIE, f: Perraudeau) (Reduced database)

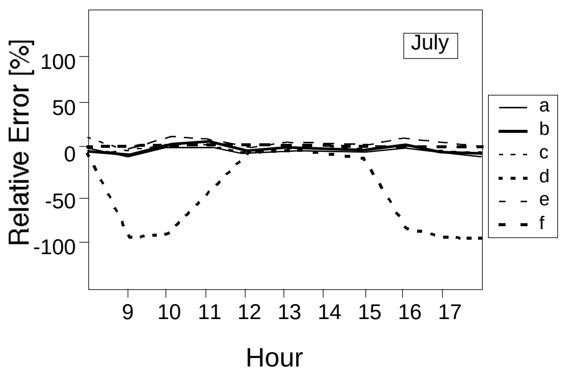

Figure 6. Relative errors for a "typical" day in July. (a: CIE, b: Perez, c: Kittler, d: Brunger, e: ASRC-CIE, f: Perraudeau) (Reduced database)

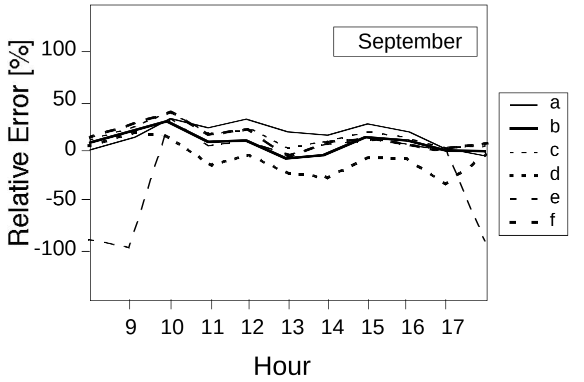

Figure 7. Relative errors for a "typical" day in September. (a: CIE, b: Perez, c: Kittler, d: Brunger, e: ASRC-CIE, f: Perraudeau) (Reduced database)

DISCUSSION

The rather short period of data collection and the resulting small set of data may not warrant a final judgement as to the relative performance of the six sky models in view of their reliability in general and their applicability in the tropical context in particular. However, if we assume that the currently available empirical data represents a good sample of the prevailing sky conditions in Singapore, the following provisional conclusions can be derived:

a) At least three of the six models (Perez, Kittler, and Perraudeau) perform satisfactorily (high correlation, low error deviation range) in the prediction of Singapore's sky luminance distribution.

b) The current data suggests the following provisional ranking among the models:

Table 3: Relative Overall Performance of the Six Sky Models with Regard to the Singapore Measured Data

Model	*Rank*
Perez, Kittler, Perraudeau	I
Brunger, CIE	II
ASRC-CIE	III

c) The models appear to perform better under cloudy conditions. To illustrate this point on a *pars por toto* basis, we compare the performance of the models for a typical day in June and July (cp. Figures 5 and 6). While the former may be considered a rather clear day, the latter is more representative of an overcast day (cp. the corresponding measured diffuse and global horizontal illuminance level in Figure 8).

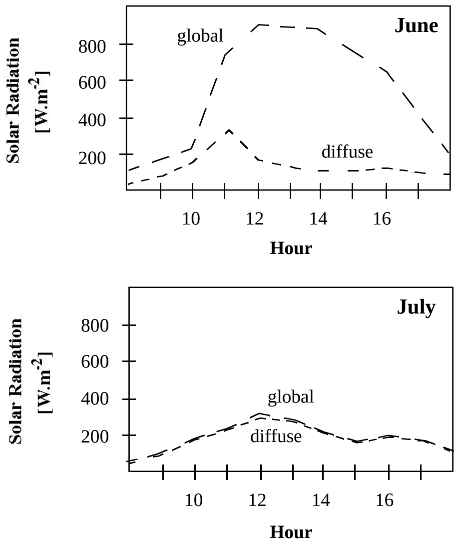

Figure 8. Measured global and diffuse irradiance on a "typical" day.

d) The majority of the models display a tendency toward overestimating the sky luminance values, particularly in the sky region further away from the sun position (cp. Figure 3).

We also compared model predictions with the original database. Due to the previously mentioned data quality concerns, we would not like to emphasise the significance of these results. Nonetheless, their considerably lower correlation levels potentially imply the necessity for the development of a specific sky luminance model for Singapore data.

A total of around 65000 pairs of measured-predicted values in the original database were used to derive the degree of correlation (r) between the measurements and the predictions of each model. The results are summarized in Table 4.

Table 4: Correlation Between Measured and Predicted Values (Original Database)

Model	*correlation (r)*
Perraudeau	0.64
Perez	0.62
Kittler	0.57
Brunger	0.57
ASRC-CIE	0.36
CIE	0.17

The mean relative errors for the original database are given in Table 5. Figure 9 shows the mean relative errors with a deviation range which contains ca. 70% of all relative error values.
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Table 5: Mean Relative Errors of the Predicted Values (Original Database)

Model	*Mean Relative Error* [%]
Brunger	-3.0
CIE	20.8
ASRC-CIE	-23.0
Perez	26.5
Kittler	29.0
Perraudeau	33.6

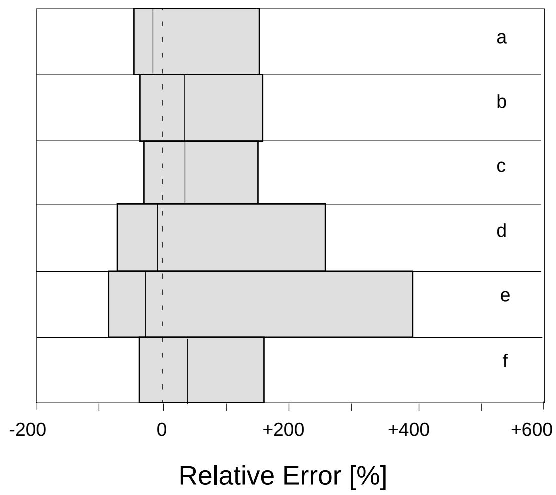

Figure 9: Mean Relative Errors with the corresponding Deviation Ranges containing ca. 70% of the relative errors (a: CIE, b: Perez, c: Kittler, d: Brunger, e: ASRC-CIE, f: Perraudeau). (Original Database)

Figure 10 shows the mean relative errors of the models as a function of the sun position (expressed as the angular distance of the relevant sky patch from the sun position).

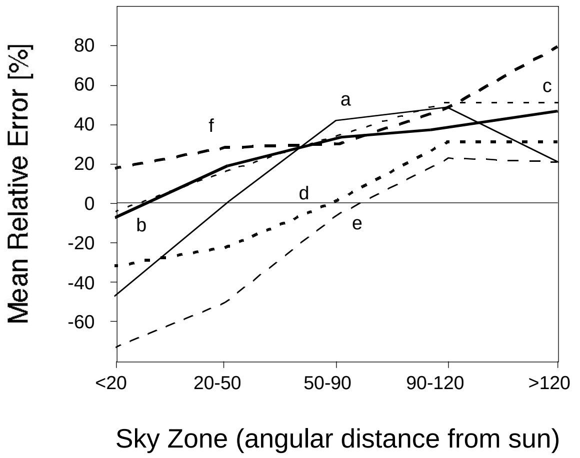

Figure 10: Mean relative error as a function of the angular distance of the relevant sky patch from the sun (a: CIE, b: Perez, c: Kittler, d: Brunger, e: ASRC-CIE, f: Perraudeau). (Original Database).

The following diagram (Figure 11) shows the measurement vs. prediction regression lines for all models based on the original database.

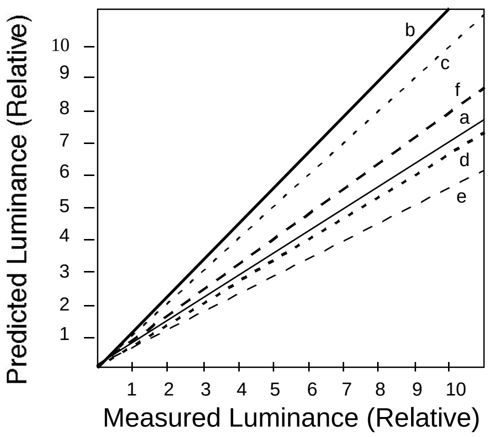

Figure 11: Measurement vs. Prediction regression lines for the six sky model (a: CIE, b: Perez, c: Kittler, d: Brunger, e: ASRC-CIE, f: Perraudeau) (Original Database).

Figures 12, 13 and 14 illustrate the daily pattern of relative errors for three typical days.

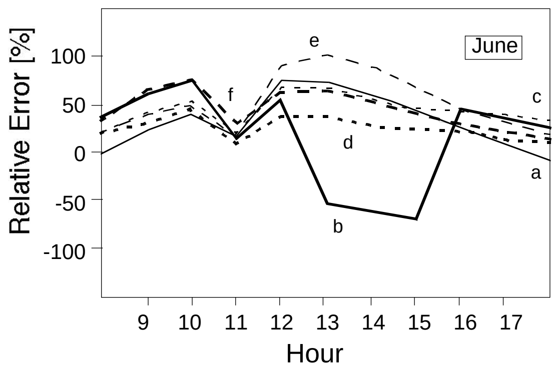

Figure 12. Relative errors for a typical day in June. (a: CIE, b: Perez, c: Kittler, d: Brunger, e: ASRC-CIE, f: Perraudeau) (Original Database)

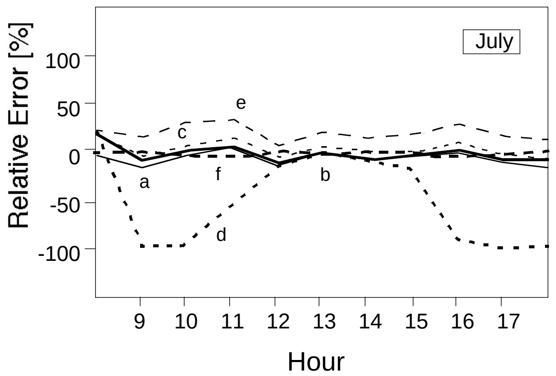

Figure 13. Relative errors for a typical day in July. (a: CIE, b: Perez, c: Kittler, d: Brunger, e: ASRC-CIE, f: Perraudeau) (Original Database)

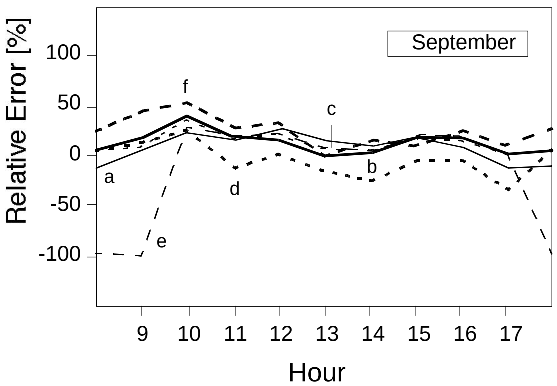

Figure 14. Relative errors for a typical day in September. (a: CIE, b: Perez, c: Kittler, d: Brunger, e: ASRC-CIE, f: Perraudeau) (Original Database)

FUTURE RESEARCH

As mentioned earlier, the results presented in this paper will have to be further scrutinized as more sky luminance data is collected. Thus, future research will involve the collection of additional data on Singapore's sky luminance distribution, the identification of the models' less satisfactory performance for near-sun and near horizon sky regions, and the re-assessment of the need for a specific prediction sky model for Singapore.

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