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Using satellite-based methods to predict daylight illuminance for subtropical Hong Kong

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Satellite-based methods are proposed to estimate global illuminance from geostationary satellite data under local climate conditions. The data used in this model are global irradiance and global illuminance collected from the International Daylight Monitoring Programme research class station in The Chinese University of Hong Kong and the visible channel data of the Geostationary Operational Environmental Satellite 9 from May 2003 to May 2005. The proposed methods consist of an indirect method, which derives global irradiance from satellite images first and then converts global irradiance to global illuminance by a luminous efficacy model, and a direct method, which derives global illuminance directly from satellite images. The root mean squared errors of hourly global illuminance are 35% and 32% for the indirect and the direct methods, respectively.

List of symbols

$C_{\max}$	normalised values of maximum satellite values
$C_{\min}$	normalised values of minimum satellite values
C_{raw}	raw pixel values
C_{sat}	normalised satellite values
D_{vc}	diffuse horizontal illuminance under the CIE Clear Sky Standard with $T_v = 2$ (k lux)
E_{e0}	solar constant (1367 W/m^2)
E_{eg}	ground-measured global horizontal irradiance (W/m^2)
$E_{eg,clear}$	standard clear sky global irradiance (W/m^2)
$E_{eg,sat}$	satellite-derived global horizontal irradiance (W/m^2)
E_{vg}	ground-measured global horizontal illuminance (k lux)
$E_{vg,clear}$	clear sky global illuminance (k lux)
$E_{vg,sat}$	satellite-derived global horizontal illuminance (k lux)
$E_e(\lambda)$	total solar irradiance at wavelength λ (W/m^2)
h	height of the site (m)
k_c	clear sky index
K_G	global luminous efficacy
k_t	clearness index
k_{vc}	illuminance clear sky index
m	optical air mass
n	cloud index
P_{vc}	parallel beam (solar) horizontal illuminance under the CIE Clear Sky Standard with $T_v = 2$
$V(\lambda)$	the value of CIE photopic sensitivity of the human eye
Z_s	solar zenith angle (degrees)
γ_s	solar altitude (degrees)
ε	eccentricity correction

1. Introduction

Lighting consumes around 17% of electricity in Hong Kong.[1] Good daylight design is of great importance for energy saving as well as

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better work efficiency. Accurate global illuminance data with a high temporal and spatial resolution is an essential input for the potential assessment, design, planning and performance monitoring of daylight-integrated systems in buildings. Traditionally, global illuminance can be collected by the means of networks of ground stations making use of illuminance meters. With the development of remote sensing technology in recent years, an alternative solution to extend the limited data set is to derive global illuminance using geostationary satellite images. In comparison with the traditional way, the satellite-based method can retrieve global illuminance data with an almost continuous spatial coverage that cannot be achieved by ground networks for economic reasons.

Satellite-based methods to predict daylight illuminance have two approaches: the indirect approach and the direct approach. In the indirect approach, the solar irradiance is first derived from the satellite images,[2–21] and then the irradiance can be converted to illuminance using luminous efficacy models.[22–27] This is applicable when illuminance data are not available from the ground measurements. The direct approach derives the illuminance by correlating the satellite data to the illuminance data collected from the ground stations.[13,28] This is good when ground measurements have the illuminance data. This paper predicts the illuminance using both these methods for subtropical Hong Kong taking into account the availability of different ground data, and then investigates the accuracy of the two methods.

2. Data

Statistical models were adopted to generate the irradiance and illuminance data from the satellite images in this study. Therefore, two kinds of data are needed, that is, global irradiance and illuminance from a ground station and satellite data, respectively.

For the ground measurements, global irradiance and illuminance were collected every 10 minutes from the International Daylight Monitoring Programme (IDMP) station at the Chinese University of Hong Kong from June 2003 to May 2005. The CIE IDMP measuring station is located on the top of the New Asia College water tower in the Chinese University of Hong Kong. The water tower itself is 30 m above ground level and it is located on a hilltop, which is approximately 150 m above sea level. The latitude and longitude of the station are 22.25°N and 114.12°E, respectively.

Global horizontal irradiance (E_{eg}) and global horizontal illuminance (E_{vg}) were measured by Pyranometer MS-64 and Luxmeter ML-020S-I/O instruments, respectively under a quality control procedure based on the CIE Guide to Daylight Measurement.[29]

For satellite data, the visible channel data of the Geostationary Operational Environmental Satellite (GOES)-9 in the same period as the ground measurement from June 2003 to May 2005 were used in this study. The GOES-9, located at longitude 155°E took one or two pictures in 1 hour over the Asia-Pacific Region. The spatial resolution of GOES-9 for southern China is about 10 km. The position of the IDMP station in the Chinese University of Hong Kong does not exactly match any of the pixels of the satellite images. This study bases the analysis on 2 × 2 pixels average containing the IDMP station (Figure 1). The four pixels were extracted from all the images from June 2003 to May 2005 to form a time serial array corresponding to the ground measurement. The quality control procedure for the satellite data used the following criteria:

- the solar altitude γ_s was beyond 4°
- the raw satellite digital counts were not equal to 0 and 255 when $\gamma_s > 4°$

The whole data set including ground measurement and satellite data was randomly

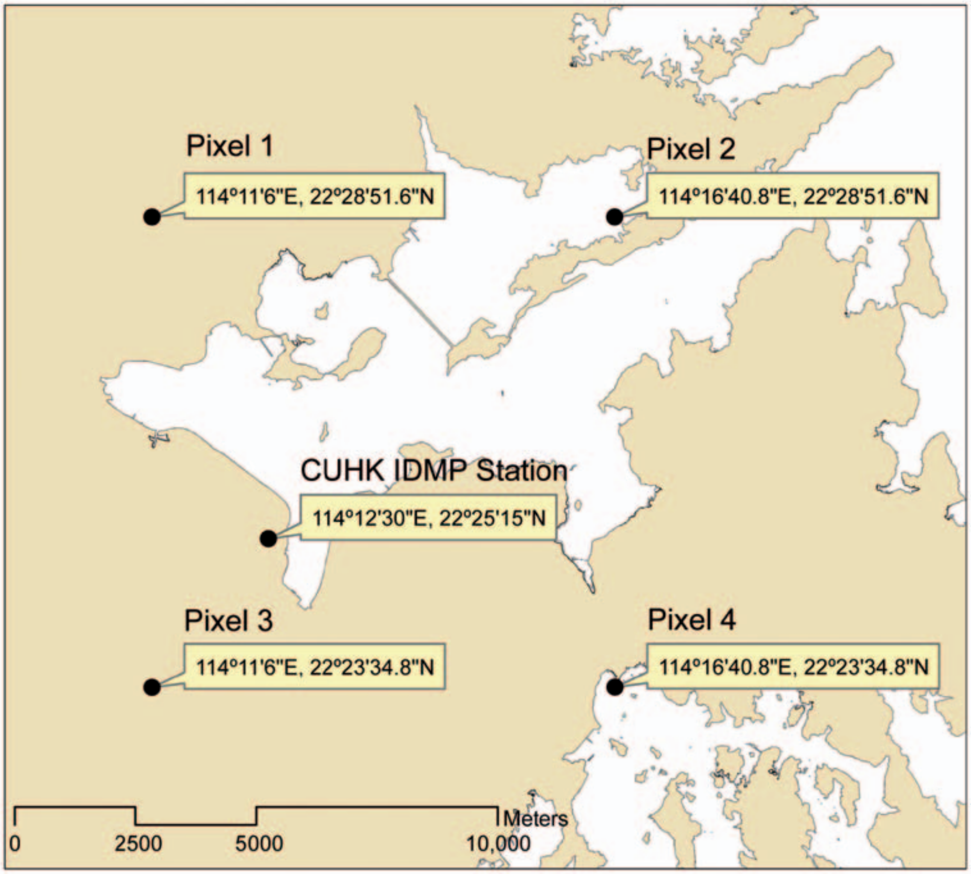

Figure 1 The 2 × 2 pixels containing the IDMP station

separated into two groups, 80% for fitting the models and 20% for assessment of accuracy.

3. Methodology

The general idea of the method in this study for the estimation of daylight illuminance from satellite images is to relate the cloud index derived from satellite images to the clear sky index/illuminance clear sky index. In the first step a cloud index is derived from the GOES-9 visible channel data to take into account the interaction of direct solar radiation with the clouds. In the second step the clear sky index and the illuminance clear sky index are calculated based on the ground-measured global horizontal irradiance and global horizontal illuminance for the indirect method and the direct method, respectively. Finally, the cloud index is correlated to the clear sky index and the illuminance clear sky index for model derivation. Figure 2 gives an overview of the algorithms used to calculate the global illuminance for both the indirect and the direct methods.

Some assumptions were made in this study. They are:

- Ground reflectance is Lambertian.
- The albedo of a cloudy atmosphere is larger than the albedo of the Earth's surface.
- One or two satellite images in 1 hour can represent the cloud information during the whole hour.

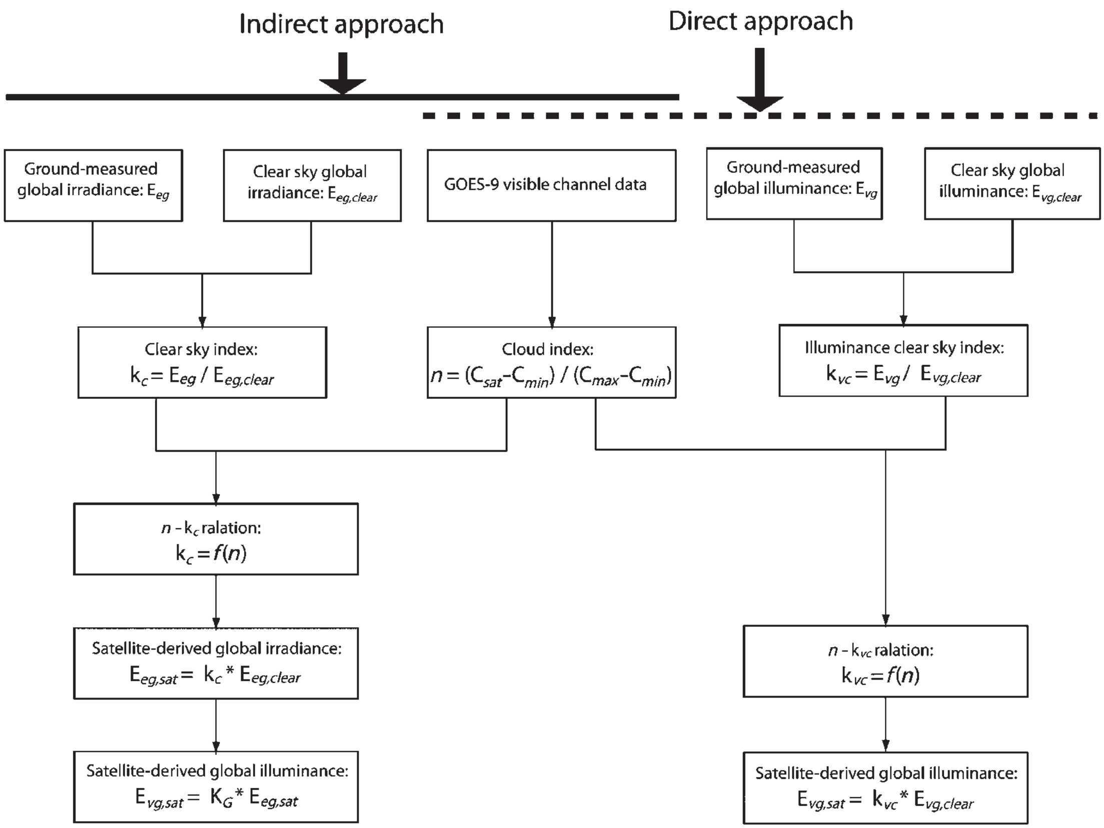

Figure 2 An overview of the algorithms for the derivation of global illuminance from satellite data: Direct approach and indirect approach

3.1 Satellite pixel value to cloud index

Figure 3 shows an example of the raw values of one pixel (22.393°N, 114.185°E) chosen for this study from June 2003 to May 2005. The gray-scale values of the GOES-9 visible channel values range between 0 and 255 representing black to white. White pixels indicate this point being covered by clouds that reflect more solar radiation, while dark pixels represent less or no clouds covering this point where solar radiation can reach the ground. This may not be true in some northern places if the ground is covered by snow. However, this study is based on a subtropical climate, specifically the subtropical climate of Hong Kong and the adjacent region where snow is rare. Therefore, the assumption that the albedo of a cloudy atmosphere is usually larger than the albedo of the Earth's surface is acceptable for this study.

The raw pixel values were first corrected for the geometric sun–earth distance and for the solar incidence as follows:[14]

$$C_{sat} = \frac{C_{raw}}{\varepsilon \cos Z_s} \quad (1)$$

where C_{sat} is the normalised satellite value, C_{raw} is the raw pixel value, ε is the eccentricity correction and Z_s is the solar zenith angle.

Then the pixel values were corrected for the so-called air mass effect and back-scattering effect.[14] In this study a simple method was used to correct for these two effects based on

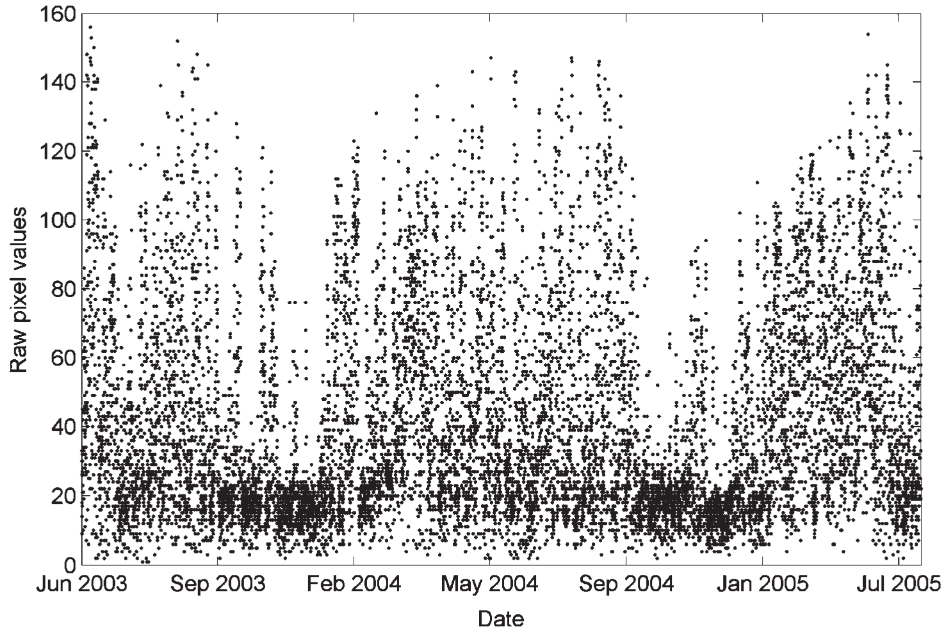

Figure 3 Satellite raw pixel values from June 2003 to May 2005 at 22.393°N, 114.185°E

the Ineichen-Perez method.[13] The solar elevation abscissa was divided into 30 bins to derive the upper and lower boundaries of the normalised pixels. The extreme 1% highest and 1% lowest values were rejected as noise values in each bin, then the highest 10% and lowest 10% points were averaged as the upper boundary and lower boundary respectively in each bin. For the back-scattering effect, the sun/satellite angle abscissa was divided into 30 bins to derive the upper boundary and lower boundary in the same way.

Finally, the two upper boundaries and two lower boundaries, taking into account air mass effect and back-scattering effect respectively, were averaged to obtain the final upper boundary and lower boundaries corresponding to the $C_{\max}$ and $C_{\min}$ respectively in Equation (2). The cloud index (n) originally proposed by Cano *et al.*[2] was then determined as follows:

$$n = \frac{C_{sat} - C_{\min}}{C_{\max} - C_{\min}} \quad (2)$$

where $C_{\min}$ and $C_{\max}$ are normalised values of minimum and maximum satellite values.

After the correction for air mass effect and back-scattering effect, the cloud indices derived from four satellite pixels surrounding the IDMP station were averaged to hourly data for further analysis.

3.2 Cloud index to global illuminance: Indirect approach

3.2.1 Clear sky index

The clear sky index is defined as:[17]

$$k_c = \frac{E_{eg}}{E_{eg,\,clear}} \quad (3)$$

where E_{eg} is hourly global horizontal irradiance measured at the ground station (W/m^2).

A standard clear sky global irradiance model proposed by Igawa *et al.*[30] was used in this study:

$$E_{eg,\,clear} = \frac{0.84E_{e0}}{m \cdot \exp(-0.0675 \cdot m)} \tag{4}$$

where E_{e0} is solar constant, 1367 W/m^2, m is optical air mass calculated by the expression introduced by Kasten and Young:[31]

$$m = \frac{1 - h/1000}{\cos Z_s + 0.50572(96.07995 - Z_s)^{-1.6364}} \tag{5}$$

where h is the height of the site in metres, Z_s is the zenith angle of the sun in degrees.

3.2.2 $n-k_c$ relation

Both the Heliosat model and the Perez *et al.*[16] model, which are the two most popular statistical models currently in use, use a $n-k_c$ relation (i.e. the relationship between the clear sky index and the cloud index) to derive the algorithms.[16,17] This study also adopted the $n-k_c$ relation for model derivation to predict the global irradiance for subtropical Hong Kong under local climate and satellite conditions. Eighty percent of the whole data set was used for fitting the model. The scatter plot (Figure 4) shows the relationship between the clear sky index and the cloud index. This shows an almost linear relationship. In the regression procedure, solar altitude γ_s was used as an additional independent variable to optimise the algorithm.

The new algorithm proposed is then:

$$\begin{aligned} k_c = {} & 0.549 - 0.370n + 0.562\sin\gamma_s + 0.262n^2 \\ & - 1.614n \cdot \sin\gamma_s + 1.133n \cdot \sin^2\gamma_s \\ & - 0.370\sin^3\gamma_s \end{aligned} \tag{6}$$

3.2.3 Global horizontal irradiance $E_{eg,sat}$

The global horizontal irradiance $E_{eg,sat}$ is then calculated by:

$$E_{eg,\,sat} = k_c \cdot E_{eg,\,clear} \tag{7}$$

3.2.4 Global irradiance to global illuminance

The satellite-derived global horizontal irradiance can be converted to global horizontal illuminance by using a global luminous efficacy (K_G) model. In simple terms, the global luminous efficacy of daylight is defined as the ratio of the global horizontal illuminance (E_{vg}) to the global horizontal irradiance (E_{eg}).

$$K_G = \frac{E_{vg}}{E_{eg}} \tag{8}$$

Mathematically, it may be written as:[22]

$$K_G = \frac{E_{vg}}{E_{eg}} = \frac{683 \int_{380}^{780} V(\lambda)E_e(\lambda)\,\mathrm{d}\lambda}{\int_0^{\infty} E_e(\lambda)\,\mathrm{d}\lambda} \tag{9}$$

where $V(\lambda)$ is the value of CIE photopic sensitivity of the human eye and $E_e(\lambda)$ is the total solar irradiance at wavelength λ. The integration is between the limits 380 nm and 780 nm as a human eye can only sense the radiant energy spectrum in that region.

Researchers have proposed several different global luminous efficacy models.[22–25,27,32] These models need different meteorological parameters or sky conditions. Among these models, the Muneer–Kinghorn model[32] only needs the global horizontal irradiance, which is one of the most common meteorological parameters measured by ground stations. As global horizontal irradiance is also the only input parameter for a satellite-based model to derive global illuminance, this study adopted the Muneer–Kinghorn[32] model to convert satellite-derived global horizontal irradiance

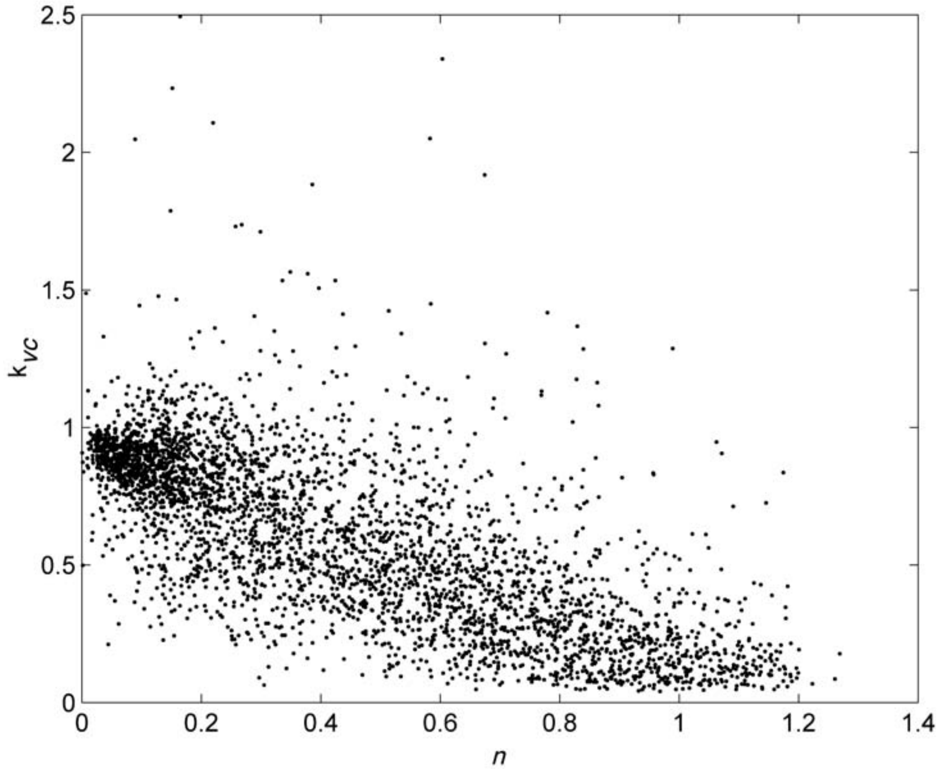

Figure 4 The clear sky index vs the cloud index

to global horizontal illuminance. Ng and Tregenza[33] assessed the Muneer–Kinghorn[32] model and other models based on the ground measurements of the IDMP station in CUHK, and concluded that the Muneer–Kinghorn[32] model provided the best approach to convert global irradiance to global illuminance for Hong Kong, especially when only the global horizontal irradiance is available. The Muneer–Kinghorn[32] luminous efficacy model is defined as:

$$K_G = 136.6 - 74.541k_t + 57.3421k_t \quad (10)$$

where k_t is the clearness index, the ratio of the global horizontal irradiance to the extraterrestrial horizontal irradiance.

Then the global illuminance predicted by the indirect method is calculated as follows:

$$E_{vg,\,sat} = K_G \cdot E_{eg,\,sat} \quad (11)$$

3.3 Cloud index to global illuminance: Direct approach

By using the indirect approach, global illuminance can be converted from satellite-derived global irradiance through a luminous efficacy model. However, there is a drawback to converting global irradiance to global illuminance by a luminous efficacy model because the transformation results in differences and inaccuracies due to luminous efficacies being affected by solar elevation, cloudiness and human vision.[34]

The $n-k_c$ relation has been proved to be a good statistical approach for deriving the global irradiance according to international applications. Likewise, the illuminance clear sky index introduced by Kittler and Danda[34] could also be correlated to the cloud index to derive the global illuminance directly since the clear sky index and the illuminance clear sky index follow the same principle.

3.3.1 Illuminance clear sky index k_{vc}

The illuminance clear sky index is defined as[34]:

$$k_{vc} = \frac{E_{vg}}{E_{vg,\,clear}} \tag{12}$$

The hourly clear sky global illuminance $E_{vg,clear}$ is obtained from:[34]

$$E_{vg,\,clear} = P_{vc} + D_{vc} \tag{13}$$

where P_{vc} is the parallel beam (solar) horizontal illuminance under the CIE Clear Sky Standard with $T_v = 2$, D_{vc} is the diffuse horizontal illuminance under the CIE Clear Sky Standard with $T_v = 2$.

3.3.2 $n-k_{vc}$ relation

Figure 5 displays the hourly average cloud index (n) versus the illuminance clear sky index k_{vc}. Like the $n-k_c$ relation, there is a linear relation between these two parameters though some points are scattered. Eighty percent of the whole data set was used for fitting the model. The scattered data could be due to the low temporal resolution of the satellite data. Using only one or two values to obtain the hourly average might cause a large error in a humid subtropical climate characterised by frequent patterns of broken cloud.

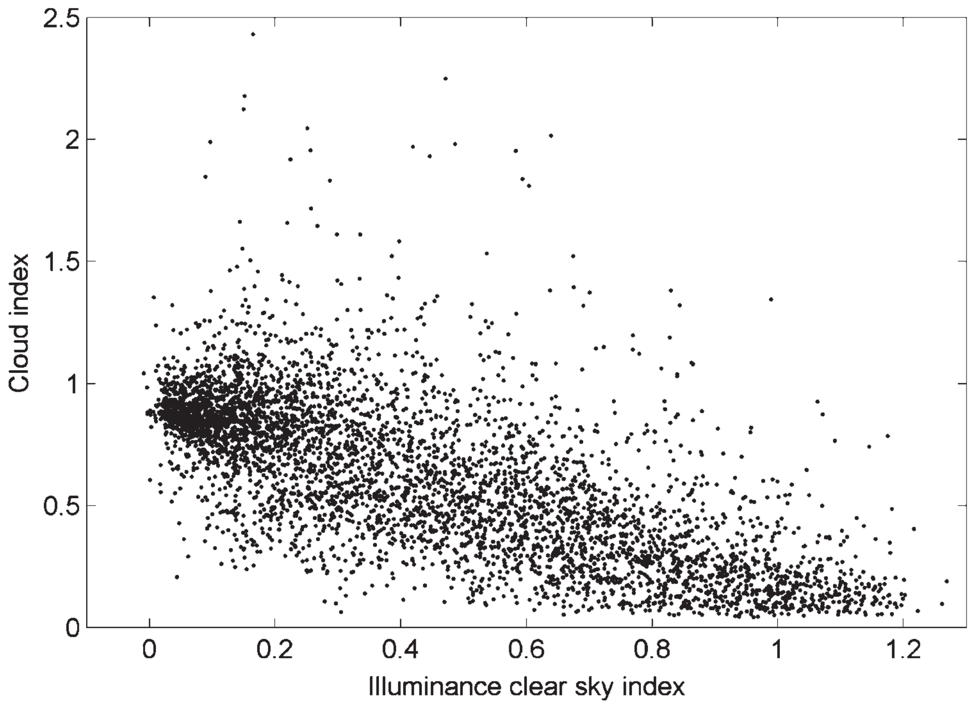

Figure 5 The cloud index vs the illuminance clear sky index

The $n-k_{vc}$ relation proposed is then as follows:

$$k_{vc} = 1.383 - 0.659n - 2.037\sin\gamma_s - 0.858n \cdot \sin\gamma_s + 3.166\sin^2\gamma_s + 0.284n^3 - 0.351n^2 \cdot \sin\gamma_s + 0.962n \cdot \sin^2\gamma_s - 1.697\sin^3\gamma_s \quad (14)$$

where γ_s is the solar altitude that was used as an additional independent variable to optimise the algorithm.

3.3.3 Global horizontal illuminance $E_{vg,sat}$

The global horizontal illuminance $E_{vg,sat}$ is then calculated by:

$$E_{vg,\,sat} = k_{vc} \cdot E_{vg,\,clear} \quad (15)$$

4. The precision of the models

Twenty percent of the whole data set was used for assessment of the models. The hourly calculated global irradiance and global illuminance values were compared to assess the precision of the models in terms of mean bias error (MBE) and root mean squared error (RMSE).

4.1 Irradiance model precision

The first step in the indirect method is to derive the global irradiance. Figure 6 shows the ground-measured irradiances versus the satellite-derived global irradiances, and Table 1 gives the corresponding MBE and RMSE values.

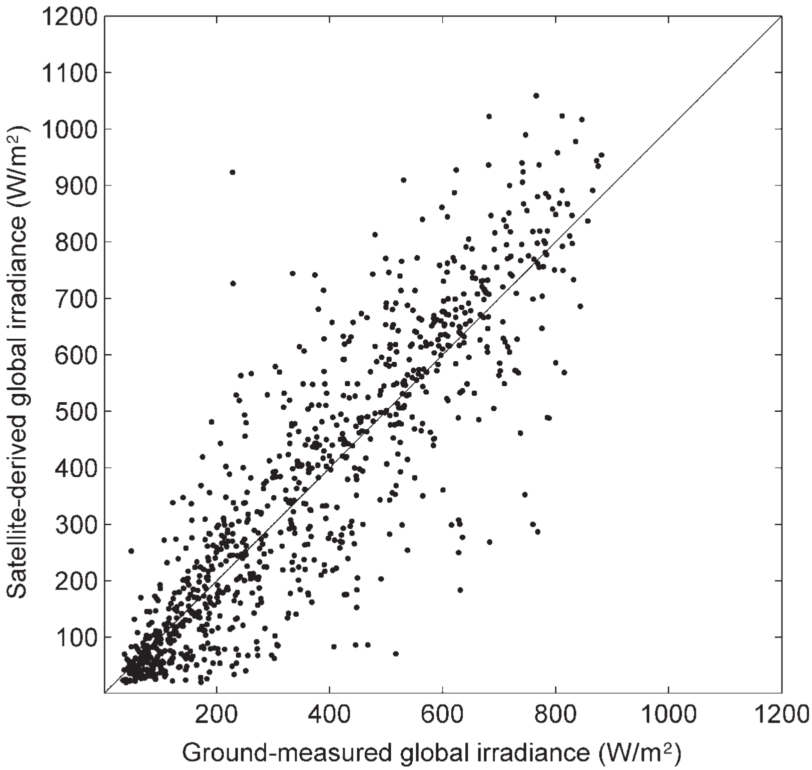

Figure 6 A comparison between hourly irradiance obtained by measurement and calculated from the model

4.2 Illuminance models precision

The second step in the indirect method is to convert the satellite-derived global irradiance to global illuminance. The direct method is to derive the global illuminance directly from the $n-k_{vc}$ relation. Global horizontal illuminances derived from the two methods were compared. Figures 7 and 8 show the ground-measured illuminances versus the satellite-derived global illuminances for the indirect and direct methods, respectively, and Table 2 gives the corresponding MBE and RMSE values.

Table 1 MBE and RMSE of the irradiance model

	MBE	% MBE	RMSE	% RMSE
Proposed model	−5	−1	119	33

5. Conclusions

This study has presented statistical models capable of deriving global horizontal illuminance for a subtropical climate from the geostationary satellite visible data. They could resolve the problem of insufficient data for daylight design where ground measurements are not available. The two models consist of an indirect method and a direct method. The choice of which method to be used in the development of a model depends, to a great extent, on the ground data available. If the ground illuminance is available, the direct method is the better choice. If only global irradiance is measured at the ground station, the indirect method could be an alternative. The indirect method derives global horizontal irradiance first using a $n-k_c$ relation, and then converts the global

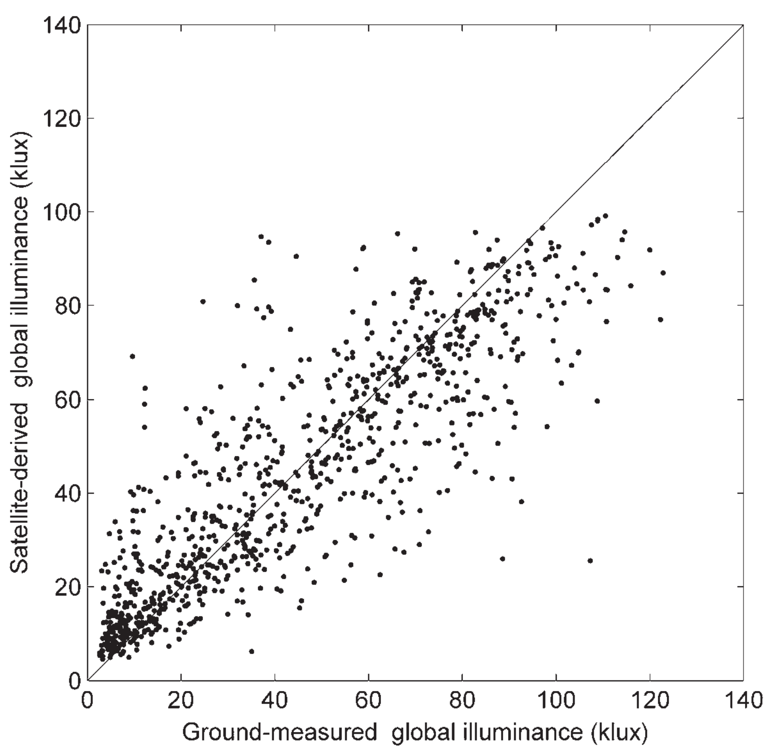

Figure 7 Estimated global illuminance vs measured global illuminance: indirect approach

horizontal irradiance to global horizontal illuminance by using a luminous efficacy model. The direct method derives the global horizontal illuminance by using a $n-k_{vc}$ relation directly.

Both the indirect and the direct methods used to derive the daylight illuminance have particular advantages and shortcomings. The direct method has better accuracy; while the indirect method only needs the global irradiance as input data, which is one of the most commonly measured meteorological parameters. The RMSE of hourly illuminance predicted by the direct method is 32%, which is comparable to the result presented by Ineichen and Perez[13] who obtained a RMSE of 31% in Geneva using a statistical model based on the Meteosat satellite. The RMSEs are relatively large compared to the accuracy of other models used to predict hourly irradiance such as the Heliosat method. The reason could mainly be due to the satellite's intrinsic error and the changeable weather and cloud pattern in a subtropical region.

Table 2 MBE and RMSE of the values of the hourly global illuminance obtained by the indirect and direct methods

Methods	MBE (k lux)	% MBE	RMSE (k lux)	% RMSE
Indirect	−0.68	−1.5	15	35
Direct	0.3	0.6	14	32

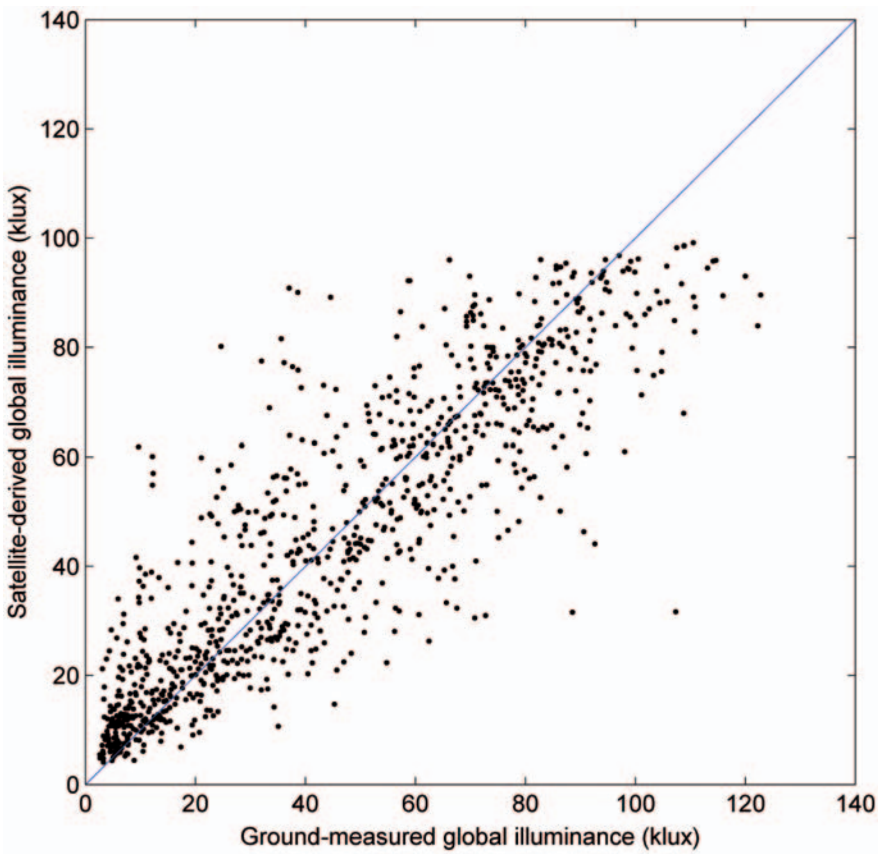

Figure 8 Estimated global illuminance vs measured global illuminance: direct approach

Although the models have been developed based on Hong Kong data, they also could be applied for neighbouring areas with a similar solar radiation climate such as southern China where the daylight data are insufficient.

There are some limitations to this study. There are no other ground-measured daylight data outside Hong Kong in subtropical southern China against which to validate the models. In addition, no high temporal and spatial resolution satellite images were available for this study. This study is based on the IDMP measurement from 2003 to 2005. During this period, only the GOES-9 data was available and that is a backup for the ailing GMS-5. The GOES-9 satellite with low spatial and temporal resolution may not catch the chaotic and rapidly changing cloud cover in a subtropical climate and thus can cause larger errors when predicting daylight data.

Future work can focus on:

(1) refining the $n-k_c$ and $n-k_{vc}$ relations taking into account other additional parameters and using other statistical methods to get better accuracy
(2) investigating if additional satellite channels may improve the performance of the models
(3) trying to derive other daylight data such as diffuse illuminance and sky types.

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