A SIMPLE ALL-WEATHER SKY RADIANCE MODEL

Ardeshir Mahdavi[1], Sokol Dervishi[1,2]
[1]Department of Building Physics and Building Ecology, Vienna University of Technology, Austria
[2]Department of Architecture, Epoka University, Tirana-Albania

ABSTRACT

This paper presents a simple all-weather sky radiance model (diffuse component). The model development was motivated by the intention to find a balance between the model's simplicity and ease of use on the one side and predictive capability on the other side. To develop the model, measured data collected at the microclimatic monitoring station of our institute (the Department of Building Physics and Building Ecology of the Vienna University of Technology) was deployed. To formulate the model, a formalism based on the concept of irradiance coefficient was used. Irradiance coefficient denotes, in percentage, the fraction of global horizontal irradiance attributable to a distinct sky patch. Thus, the developed model can be used to estimate the contributions of a set of discrete sky patches toward the overall global horizontal irradiance. The irradiance coefficient is estimated as a function of a number of salient variables related to sky Clearness Factor (an original function of the sky Clearness Index), angular distance of the observed patch from the sun patch, and observed patch altitude. The performance of the resulting model was assessed against a separate set of measurements. The comparison displayed good agreement.

INTRODUCTION AND BACKGROUND

Sky radiance models are of fundamental importance in a number of scientific and engineering applications, including the use of performance simulation tools towards supporting the design and operation of energy-efficient and sustainable buildings. Likewise the design and configuration of building-integrated renewable energy systems such as solar-thermal collectors and photovoltaic elements require reliable sky radiance models.

Previous research in this area has led to the development of a number of models used for generating sky radiance distribution maps. The isotropic model (Liu and Jordan 1960) assumes that all diffuse radiation is distributed uniformly over the sky dome. In case of anisotropic models, typically three components of the diffuse radiation are considered (see, for example, Hay and Davies 1980, Klucher 1979, Brunger and Hooper 1993, Harrison and Coombes 1988, Skartveit and Olseth 1987, Reindl et al. 1990b, Perez et al. 1990). These are, the circumsolar region consisting of the diffuse radiation near the solar rays, isotropic radiation uniformly emitted from the rest of the sky, and horizon brightness (mostly pronounced on clear days).

Harrison and Coombes (1988) introduced a sky radiance distribution model, which utilized the opaque cloud cover as the main independent variable. Brunger and Hooper (1993) proposed a formula for the calculation of the sky radiance distribution, whereby different sky conditions (from clear sky to overcast sky) could be accommodated based on the consideration of cloud ratio and the atmospheric clearness index. Kittler et al. 1997 classified sky conditions into 15 categories and proposed numerical equations to derive sky radiance distribution. This model was adopted as CIE Standard General Sky (CIE 2003). Li et al. 2002, Cucomo et al. 2007, and Chirarattananon et al. 2007 evaluated various mathematical models to predict global solar radiation on vertical surfaces. Notton et al. 2006 compared mathematical models for predicting incident solar irradiation on inclined surfaces based on measurements. Eseev and Kudish 2009, Gueymard 2009, Loutzenhiser et al. 2007, and Padovan and Del Col 2008 compared different models to predict the global solar radiation on inclined surfaces in different locations.

Despite past efforts, further studies in this domain are still necessary. In our previous studies, we have found that certain highly detailed models with multiple coefficients perform below expectation, if these coefficients are not calibrated based on local high-resolution long-term measurements (Mahdavi and Dervishi 2010, Orehounig et al. 2011). In these studies, which used long-term high-resolution measurments conducted in Vienna (Austria), the range of errors was rather high for all models compared. Even for the best-ranked option, no more than 64% of the results had a relative error of less than ±20%.

In our view, these experiences highlight the desirablitly of a balanced approach pertaining to models' algorithmic simplicity and ease of use on the one side and its predictive capability on the other side. In this context, it is important to follow to the general spirit of scientific inquiry, in which the continuous and rigorous testing and evaluation of existing models are energetically encouraged. In the building performance simulation research community, we should be careful not to display an *a priori* reluctant attitude, every time existing models are critically examined. Critical contributions pertaining to the extent of the validity of the currently deployed models are often encountered with two kinds of reactions. In the specific domain relevant to the present contribution, the fidelity of the underlying observations is at times questioned without proper reasoning. Moreover, it has been suggested that data of one specific location cannot be the grounds to question the validity of existing models (even though it appears that data from one location is sometimes conveniently used to "validate" a model).

For the purposes of this paper, we can address the former comment by referring, amongst other things, to the systematic and long-term nature of our measurements, the presence of sensor redundancy, and the conducted extensive data quality check (see, for instance, the details in the "model development" section below). As to the latter point, no unusual circumstance applies to the location of the measurements quoted. The problem appears to lie in certain misunderstanding as to what constitutes scientifically a "validation". Likewise, the notion of an independent (preferably double blind) model validation seems to be still not well-understood, as occasionally the papers by the model developers are quoted as proof the models' validity.

We specifically mention here this tendency toward suppressing contributions with "non-conformist" model observations with some emphasis, as it has manifested itself also in other instances and is a detriment to progress in our field. For example, in other studies, we addressed the performance of a large number of models to derive the diffuse component of solar irradiance based on global horizontal irradiance data (Dervishi and Mahdavi 2012, Vazifeh et al. 2013). In this case too, the comparison was conducted using measurement data from Vienna. The study implied that three of the models considered (Reindl et al. 1990, Erb et al. 1982, Orgill and Holland 1977) reproduced measurement results more accurately. But none of the models performed satisfactorily, if we, for example, would follow the formulation in ASHRAE 2002. Thereby, a models' performance is considered acceptable, if the MBE is less than ±10% and CV(RMSE) within ±30% (for hourly measurements). In the above case, almost half of the results involved a relative error of at least ±20%.

Nonetheless, as mentioned before, our main objective here is not to present a model that can be conclusively shown to surpass all existing models in predictive accuracy (this would be obviously an unjustified claim for a model developed based on data from one location). Rather, the aim is to explore a balanced approach pertaining to models' algorithmic simplicity and ease of use on the one side and its predictive capability on the other side. Our intention in model development was to generate a detailed (multi-patch) sky radiance distribution map (for the diffuse component of solar radiation) based on a minimum set of input data such as patch and solar altitude, global horizontal irradiance, etc.

Toward model development, we utilized a formalism based on the concept of irradiance coefficient (Mahdavi and Dervishi 2012). Irradiance coefficient denotes here, in percentage, the fraction of diffuse horizontal irradiance attributable to a distinct sky patch. Thus, the developed model can be used to estimate the contributions of a set of discrete sky patches toward the overall global horizontal irradiance.

The irradiance coefficient is estimated as a function of a number of salient variables related to sky Clearness Factor (an original function of the sky Clearness Index), angular distance of the observed patch from the sun patch, and observed patch altitude. Even though the model development was based on data from one location (microclimatic monitoring station of the Department of Building Physics and Building Ecology of the Vienna University of Technology, Austria), it is – in principle – applicable to other locations: Neither the selected formalism nor the model's salient independent variables would preclude its application on a broad geographical basis.

The performance of the resulting model was assessed against a separate second set of measurements, which includes a variety of different sky conditions. The comparison displayed good agreement, implying that the proposed model can be used to estimate solar irradiance on variously inclined surfaces with reasonable accuracy.

MODEL DEVELOPMENT

The empirical basis of the model comparison was long-term measurements at the microclimatic monitoring station of the Department of Building Physics and Building Ecology (Vienna, Austria). Measurements included radiometric data such as global and diffuse horizontal global irradiance, vertical global irradiance for four cardinal orientations, and sky radiance distribution of 145 discrete sky patches using a sky scanner. Moreover, typical weather data such as air temperature and relative humidity, wind speed and direction, atmospheric pressure, and precipitation were collected via our Department's weather station.

To derive the sky radiance model, a first database containing measured values over a one-year period (01.08.2010 to 30.07.2011, first 15 days of each month) was established. To evaluate the predictive performance of the developed model, a second database of measured irradiance and illuminance values was used, covering the same period, but using the second 15 days of each month. Measurements were performed every 15 minutes during the daylight hours, covering a variety of sky conditions, from sunny, to partly cloudy, to overcast. The specifications of the instrumentation and sensors are given in Table 1.

The collected data was statistically analyzed to explore the relationship between Irradiance Coefficients (IC in %) and candidate influencing parameters. Thereby, several variables were taken into consideration, including the Clearness Factor (CF), Angular Distance of the sun and the path (ζ), and Patch Altitude (h_p). The statistical analysis resulted in a simple algorithm for the calculation of luminous efficacy as a function of the above variables. Subsequently, calculations based on this algorithm were compared with data from the aforementioned second set of empirical measurements.

Table 1
Overview of the instrumentation specifications

Instruments	Information
Global and Diffuse irradiance (Sunshine pyranometer SPN1)	Overall accuracy: ±5% daily integrals, ±5% ±10 $W.m^{-2}$ hourly averages ±8% ±10 $W.m^{-2}$ individual readings. Resolution: 0.6 W.m =0.6 mV, range: 0 to > 2 000 $W.m^{-2}$ sunshine status threshold: 120 $W.m^{-2}$ in the direct beam, temperature range: -20 to +70 ° C, accuracy: Cosine Correction ±2% of incoming radiation over 0-90° Zenith angle, accuracy: azimuth angle ±5% over 360° rotation, Response time <200 ms
Weather station	Outdoor temperature: Absolute Error: < 0.3 K; Temperature range: -30 to +70 ° C; Response time < 20 s (≥ 1.5 $m.s^{-1}$). Outdoor relative humidity: Absolute Error: < ±2%; Humidity range: 0 to 100 %; Response time < 10 s (≥ 1.5 $m.s^{-1}$). Wind speed: Absolute Error: <1%; Wind speed range 0 - 75 $m.s^{-1}$
Sky Scanner	Radiance: sensitivity: 300 $W.m^{-2}$ sr^{-1}, resolution: 1.0 $W.m^{-2}$. sr^{-1}, entire sky scanning time: 4 min/145 points , resolution (angle): 0.0036°, accuracy (angle): 0.2°
Pyranometer (GSM 10.7)	Global irradiance (horizontal and vertical): Range: 0 -1300 W. m^{-2}; Spectral range 380 nm-2800 nm; Temperature range -20 to +60 ° C; Accuracy cosine correction <3%; Linearity <1%; Absolute Error <10%

To generate the sky radiance model, a formalism involving the concept of Irradiance Coefficient (IC) was applied (Mahdavi 2012) Irradiance Coefficient is defined here as the ratio of irradiance due to the sky patch *i* (E_i) divided by the horizontal diffuse irradiance (E_{diff}) at a certain point (see equation 1).

Collected data was made subject to a comprehensive quality check. Specifically, measurements at very low sun altitudes (less than 5 degrees) and those involving very low global horizontal irradiance values (below 50 $W.m^{-2}$) were excluded, given the uncertainty in the sensor accuracy for this radiation intensity range. Subsequent to the data quality check, 6293 full sky scans in the first database and 6141 full sky scans in the second database were included in the study. Note that each sky scan includes 145 distinct patch radiance measurements (see Table 2 for the specification of the center points of these patches in terms of patch azimuth and altitude data). Hence the model development and evaluation datasets include a total of roughly 1,803.000 measured radiance values.

$$IC_i = E_i \cdot E_{diff}^{-1} \tag{1}$$

Given measured patch radiance values, horizontal irradiance values for each patch were derived based on well-known algorithms (Tregenza and Waters 1983). Note that the resulting sky radiance model accounts for the diffuse portion of the global horizontal irradiance. The direct contribution of solar radiation can be computed separately based on available algorithms (Igawa et al. 1999). Thus, the developed model can be used to estimate the contributions of a set of discrete sky patches toward the overall diffuse horizontal irradiance.

We studied patch-based IC values in the first database toward identification of potential influencing parameter. This exploration yielded a number of interesting results. First, for clear sky conditions, a strong relationship (see Figure 1) between Irradiance Coefficients and the term sin (ζ/2), which involves the Angular Distance of the sun and the patch (ζ). Clear sky conditions in this case refer to a Clearness Index (k_g) of more than 0.8. Here, k_g denotes the clearness index as per the following equation (Reindl et al 1990).

$$k_g = \frac{E_e}{E_0 \cdot \sin(\alpha)} \tag{2}$$

In this equation, E_e denotes the global horizontal irradiance, E_0 stands for solar constant, and α refers to solar altitude.

Moreover, the analysis of the first data set revealed, for cloudy sky conditions, a relationship between IC and patch altitude (h_p). Figure 2 shows this relationship in terms of mean IC values for different patch altitudes under cloudy sky conditions (k_g less than 0.2).

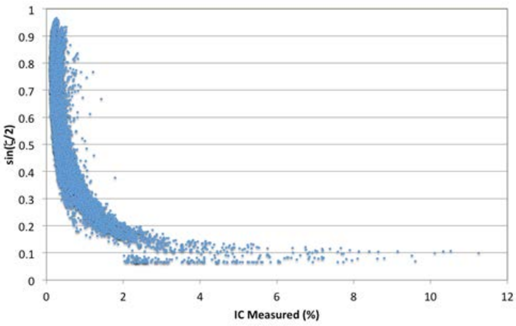

Figure 1 The relationship between measured irradiance coefficients (%) and sin (ζ/2) for clear sky conditions, first database.

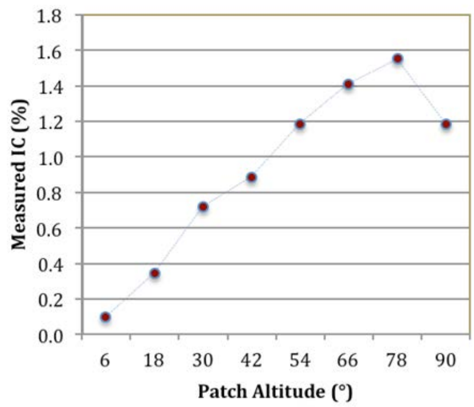

Figure 2 Mean IC values for different patch altitudes under cloudy sky conditions.

These observations provided the basis of our simple diffuse sky radiation model, consisting of two expressions, capturing the effects of sun-patch angular distance (ζ) and patch altitude (h_p) respectively. In contrast to a number of previous models, and in the interest of a compact algorithmic formulation, we decided not to define discrete instances of sky conditions in view of clearness. Rather, we developed a continuous function, whereby the variable Clearness Factor (CF) represents the applicable sky condition in the model (Mahdavi 2012) CF is an original derivative function of Clearness Index (k_g) as per the following equation (Equation 3):

$$CF = \sqrt{\log(k_g \cdot 10)} \tag{3}$$

Thus, the Irradiance Coefficient of the i-th patch (IC_i) is given by

$$IC_i = a + b \tag{4}$$

The terms a and b in the above equation are defined as follows:

$$a = \frac{CF}{\sin(\zeta/2)\cdot 2\left[\sin(\zeta/2)\right]^2 + \left[0.2/(\zeta/2)\right]} \tag{5}$$

$$b = 2 \cdot \sin(h_p) \cdot CF - 0.8 \cdot CF / (1 + \cos(h_p)) \tag{6}$$

Table 2
Patch center azimuth (α_p) and altitude (h_p) data as deployed in the sky scanner

h_p	α_p											
90												
78	0	60	120	180	-120	-60						
66	-30	-60	-90	-120	-150	180	150	120	90	60	30	0
54	0	20	40	60	80	100	120	140	160	180	-160	-140
	-120	-100	-80	-60	-40	-20						
42	-15	-30	-45	-60	-75	-90	-105	-120	-135	-150	-165	180
	165	150	135	120	105	90	75	60	45	30	15	0
30	0	15	30	45	60	75	90	105	120	135	150	165
	180	-165	-150	-135	-120	-105	-90	-75	-60	-45	-30	-15
18	-12	-24	-36	-48	-60	-72	-84	-96	-108	-120	-132	-144
	-156	-168	180	168	156	144	132	120	108	96	84	72
	60	48	36	24	12	0						
6	0	12	24	36	48	60	72	84	96	108	120	132
	144	156	168	180	-168	-156	-144	-132	-120	-108	-96	-84
	-72	-60	-48	-36	-24	-12						

(4

To generate the (diffuse) sky model based on these equations, the following procedure is to be followed:

- First, a sample of patches is to be selected that represent the entire sky dome. A possible option would be to use the same discrete patches for which the sky scanner obtains the measurements (see Table 2). However, as long as the entire sky dome is represented, other selection options (including a smaller or larger number of patches) are also permissible.
- Second, IC values are to be computed for all selected patches based on equations 4, 5, and 6. While using Equation 5 to compute the value of the term a, for all angular distance values less than 5 degrees, a value of 5 degrees should be used.
- Third, the sum total of IC values as per the above-described calculation (equations 4 to 6) might slightly deviate from the expected 100%. Hence, IC values must be modified according to a simplified normalization process. Thereby, the difference between the calculated IC sum of all patches and 100% is to be equally distributed amongst all patches.

MODEL EVALUATION

To communicate a sense of the model performance, Figure 3 and 4 show the correlation between measured and estimated IC values for the first and second database respectively. Given the stochastic nature of sky conditions (involving a host of complex phenomena pertaining to weather conditions, cloud cover and distribution, humidity and air quality circumstances), large deviations between calculations and measurements at the patch level are to be expected. This explains the rather wide scattering of the data points in Figure 3 and 4.

Nonetheless, the proposed simple model achieves – despite patch-level deviations – a fairly high overall degree of correlation. This generally good performance can also be documented, if we consider the Mean Bias Difference (MBD as computed per Equation 7), which denotes the mean relative deviation of measured (M_i) and computed (C_i) patch-based ICs.

$$MBD = \frac{\sum_{i=1}^{n} \left(\frac{M_i - C_i}{M_i}\right)}{n} \cdot 100 \quad (\%) \tag{7}$$

As applied to the second data set, MBD amounts only to 7.1 %. More importantly, the achieved level of congruence between measurements and calculations is not reduced by any means, once the model is applied to data that was not considered in the model development phase (second data set, Figure 4).

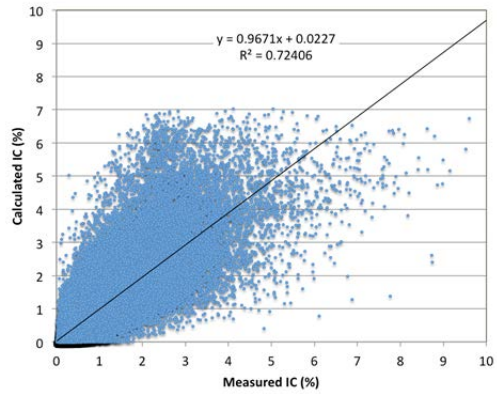

Figure 3 Measured versus calculated irradiance values for sky patches for the first data set

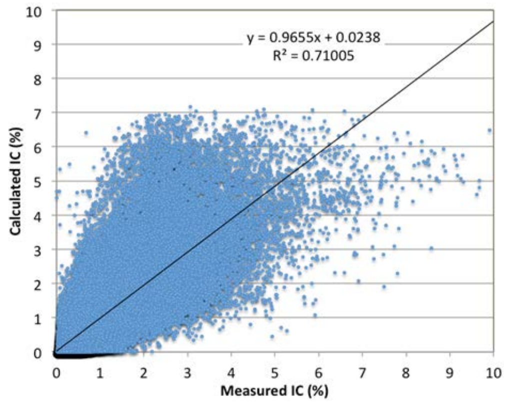

Figure 4 Measured versus calculated irradiance values for sky patches for the second data set

CONCLUSION

Evaluation of buildings and their energy systems must consider solar radiation. Toward this end, information on sky radiance is essentially important. As detailed sky radiance maps are available only for a limited number of locations, methods and models are needed to drive such detailed (patch-based) sky radiance maps computationally from more readily available global horizontal irradiance data. In this context, the present paper introduced an approach to generation of detailed sky radiance models in terms of patch-based Irradiance Coefficients. The proposed model uses a few readily available input data (patch altitude, sun-patch angular distance, sky clearness). Model predictions display, at the level of individual sky patches, rather large deviations from the measurements. However, the general tendency of the predictions shows a good agreement with measurements conducted in Vienna, Austria. Hence, a good predictive performance is likely, if the model is applied to compute aggregate parameters (such as diffuse and global irradiance on variously inclined building surfaces). This assertion as well as the question of the applicability of the proposed model to other locations shall be examined within the framework of future research activities.

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