Robust Sky Modelling Practices in Daylighting Simulations

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ABSTRACT: The demand for more sustainable building practices prompted the use of more analytical tools in the design processes. This paper addresses a need to compare various sky models used in daylighting practices. The sky models can be mathematical or image based; they can be generic or measurement based. The selection of the right model depends on the scope of the simulation. It is recommended to use generic CIE models only for basic comparisons. When generated or calibrated with diffuse and direct irradiance values, CIE, Perez, and image based sky models yield to comparable results. Image based sky models are most useful to capture the local conditions that include the complexities of clouds and solar corona, surrounding urban fabric and forestry.
Keywords: daylighting, simulation, CIE sky models, Perez All-Weather Sky model, image based sky models.

INTRODUCTION

Performative feedback into the design workflows can help architects to improve the design decisions that are in flux particularly in the early phases of design. Evaluating the predicted performance of designs in a timely manner will reduce the undesirable outcomes that might require post construction alterations and interventions. Traditionally, building performance simulation tools were used by a limited number of experts; and they were deployed in later stages of design to evaluate performance when most of the design decisions were finalized. However, this has changed drastically in the recent years. Designer friendly graphic user interfaces along with advancements in building performance simulation capabilities facilitated a change towards adoption of simulations as part of design workflows.

From a technical perspective, the surge of utilization of simulations within design workflows raises concerns about the quality of the simulations that are performed by users that have varying levels of underlying expertise and education. Many end users are able to generate lighting visualizations and calculations. However, a study demonstrates that early users struggle to achieve accurate simulation results even within simple workflows (Ibarra and Reinhart, 2009). One major issue that pose problems for successful wide-spread adoption of performative feedback into design workflows is that users may not have adequate understanding of the algorithms, assumptions, and limitations of the simulation tools and techniques they are using.

SKY MODELLING

This paper focuses on daylighting design processes and simulations. The development of new generation of simulation tools that provide accessible graphic user interfaces to software such as Radiance (Ward, 1994) improved the accessibility of this software that is otherwise notoriously known for its steep learning curve. A survey conducted among design teams that have an interest in sustainability demonstrated a strong bias (over 50%) towards Radiance-based simulation tools (Galasiu and Reinhart, 2008).

The accuracy of daylighting simulations is particularly dependent on the luminance composition of the sky. Sky luminance depends on a series of geographic, meteorological and seasonal parameters, such as latitude, atmospheric turbidity, water mass, and cloud cover. The currently available sky models can be divided into three categories:

- Generic CIE models defined by International Commission on Illumination (CIE, 2003);
- Arbitrary skies defined by Perez All-Weather model (Perez et al., 1993); and
- Image based models that incorporate High Dynamic Range (HDR) luminance values of the sun and the sky (Stumpfel et al, 2004).

CIE skies are mathematical models that represent the average sky brightness patterns as smooth continuous functions that provide the best fits to models developed from long-term daylight measurements. The relative luminance of any patch in the sky is defined through the angle between the patch and the zenith (in overcast skies), and the angle between the patch and the sun (in non-overcast skies). Although CIE (2003) defines 15 different sky models that vary from overcast to cloudless skies, three CIE classical skies are commonly used in simulations: CIE Overcast, Clear, and Intermediate skies (Moon and Spencer, 1942; Kitler, 1967; ISO/CIE, 1996; Nakamura et al., 1985). The basic CIE models are generic as they require only location, date, and time as input. CIE models can also be defined as measurement based if they include direct and diffuse irradiance data (W/m^2).

Perez All-Weather skies are measurement based mathematical models that represent luminance distribution values as functions of meteorological parameters such as the direct normal and diffuse horizontal irradiance. The magnitude and spatial distribution of cloud patterns, such as the solar elevation, sky clearness, and sky brightness indices are implicitly modeled. Perez sky models are particularly utilized for annual daylight simulations as the irradiance data is readily available in hourly weather files for a large number of locations around the world.

Image based skies are the High Dynamic Range (HDR) fisheye images of the sky dome. The actual sky luminance distributions are far more complex than the mathematical sky models. Complexity of clear sky distribution is pertinent to the modelling of the circumsolar region, which significantly varies in size and intensity with the turbidity and water mass. Complexity of cloudy sky distributions is pertinent to rapid changes around the boundaries of clouds in an actual sky. The approximations in mathematical models create varying levels of uncertainty in the simulation processes. HDR fisheye images of the sky can be used to capture the cloud distributions and the circumsolar region. The luminance information stored at a pixel level in an HDR photograph is mapped as a sky dome through an Image Based Lighting (IBL) technique (Debevec, 2002, 2005; Inanici, 2010).

There is a particular need to expose the difference among sky models that are used in daylighting simulations today. The common pitfalls observed frequently among users are listed here:

- A generic sky type (e.g. CIE clear sky) is assumed by visual observation, and simulations are performed with that sky with the expectation that the simulation results would align with physical measurements.
- A CIE sky type is used to compare a simulation result from an annual simulation computation. Perez sky model is usually employed in annual calculations as sky models are derived from irradiance data extracted from weather data files. It is also important to note that a Daylight Coefficient (DC) technique (Tregenza and Waters, 1983) is used in annual simulations to manage the computation time. Therefore, there are discrepancies between point at a time and annual simulation techniques, where point in time simulations provide better accuracy with the cost of increased computation.
- The surrounding is not modelled properly. The surrounding urban fabric and vegetation will impact daylight availability either by blocking portions of the sky or reflecting light. The surrounding should be explicitly modelled when using mathematical models. The impact of the surrounding is captured and incorporated in the model without explicit geometric and material modelling when using image based models.

The objective of this paper is to study and compare the accuracy and appropriateness of various sky models used in research and practice. Guidelines are provided.

SETTING AND METHODOLOGY

Two settings with a toplighting and a sidelighting design strategy are simulated with point-in-time simulation techniques to perform a comparative analysis utilizing mathematical and image based sky models. The sidelit space has a south facing window. The toplit space has two roof monitors. The floor, wall, and ceiling materials have 20%, 50%, and 70% reflectivity (Figure 1).

The measurement based sky models are generated from data collected in situ. HDR images of the sky dome at a relatively unobstructed location is collected for six months from December and June (winter solstice to summer solstice) at 47° N latitude. Data collection took place one day of the month from early morning hours to sunset at 15 minute intervals. The database has 306 HDR images of the sky dome. The HDR image collection is done in conjunction with in-situ global illuminance measurements and irradiance measurements at a local weather station. Due to the brevity of this paper, 4 instances are selected for simulations: one cloudy, one clear, and two partly cloudy skies. These skies are representative of various sun angles and naturally occurring sky types (Table 1). For each instance, 4 different sky models are generated:

- CIE sky defined by location, date, time, and a sky type (referred as CIE_{basic} hereafter);
- CIE sky defined by location, date, time, sky type, and direct horizontal irradiance and diffuse horizontal irradiance (*gensky* –B –R option). It is referred as CIE_{BR} hereafter. Reindl et al. (1990) method is used to split global irradiance values into direct and diffuse components (*gen_reindl*);
- Perez all-weather sky defined by location, date, time, direct normal irradiance and diffuse horizontal irradiance (*gendaylit* –W).
- HDR images of the sky are collected using a Canon EOS 5D camera and a Sigma 8 mm F3.5 EXDG fisheye lens that has 180° angle of view and equi-angle projection properties. Multiple exposure photographs are captured with white balance and ISO settings of ‘daylight’ and ‘100’, respectively.

The image capture, post processing, and calibration procedures are summarized as follows: Under cloudy sky conditions, sky images are taken with a fixed aperture size (f/5.6), and varying the shutter speed.

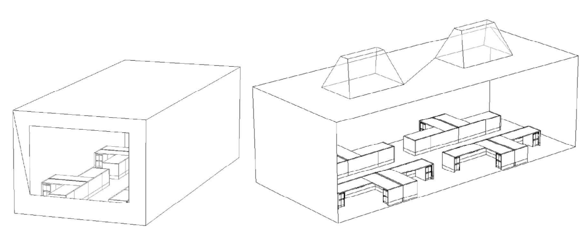
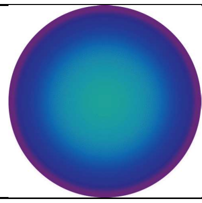
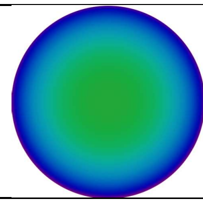
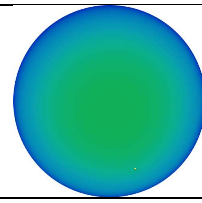
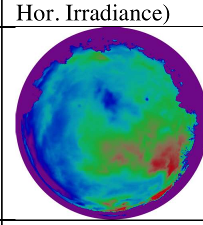
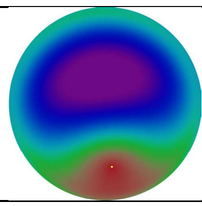
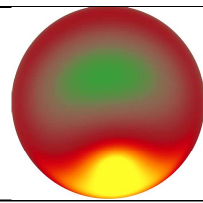
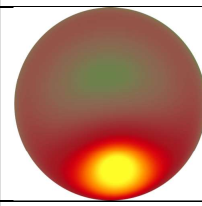
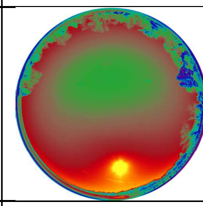
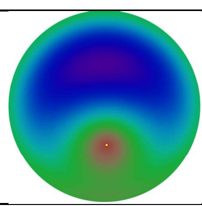
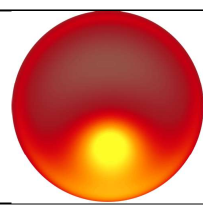
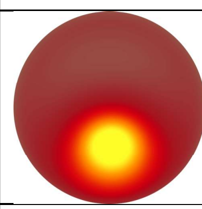
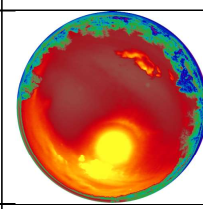
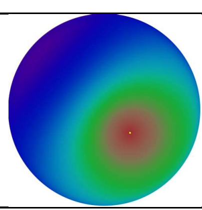
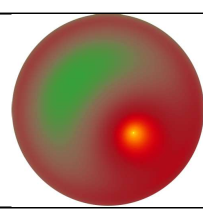
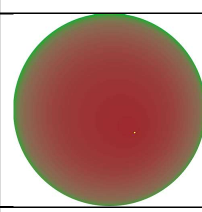
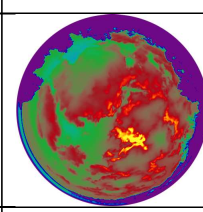
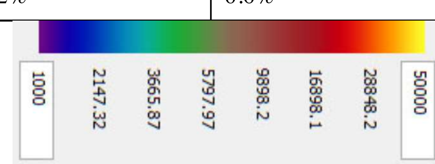


Figure 1 The sidelit and toplit settings used for simulations (room dimensions 6 x 14 x 4.5m)

Table 1: Sky conditions chosen for the simulation

Model	by date and time	derived from solar radiation measurements		
	CIE_{Basic}	CIE_{BR} (sky with Direct Hor. Irradiance and Diffuse Hor. Irr.)	Perez sky (with Direct Nor. Irradiance and Diffuse Hor. Irr.)	Image based HDR sky model (calibrated with Direct and Diffuse Hor. Irradiance)
Jan 31 11:00 				
Simulated Hor. Illuminance	7,242 lux (Overcast sky)	10,533 lux (Overcast sky –B –R)	10,447 lux	10,445 lx
Measured Hor. Illuminance		10,527 lux	10,527 lux	10,527 lux
Error %	31%	0.05%	0.8%	0.8%
Feb. 20 12:00 				
Simulated Hor. Illuminance	40,964 lux (Clear sky)	60,609 lux (Clear sky –B –R)	60,420 lux	61,170 lx
Measured Hor. Illuminance		61,462 lux		
Error %	33%	1.4%	1.7%	0.5%
April 25, 12:00 				
Simulated Hor. Illuminance	69,897 lux (Clear sky)	100,504 lux (Clear sky –B –R)	99,239 lux	100,179 lx
Measured Hor. Illuminance		100,527 lux		
Error %	31%	0.5%	1.7%	0.8%
June 22, 10:30 				
Simulated Hor. Illuminance	20,950 lux (Intermediate sky)	34,258 lux (Int. sky –B –R)	33,987 lux	34,182 lx
Measured Hor. Illuminance		10,527 lux		
Error %	39%	0.4%	1.2%	0.6%
Sky luminance (cd/m^2)				

Under sunny and partly cloudy conditions, a neutral density filter (Kodak Wratten 2 Optical Filter ND3) is applied to the camera. Sky images are taken with two different aperture sizes (f/4.0 and and f/16), and varying the shutter speeds in order to be able to capture a wider luminance range. Each aperture was initially processed separately to form partial HDR images using Photosphere (Ward, 2004). The vignetting effect is significantly different for f/4.0 and f/16. After individually correcting the vignetting for each aperture, images are fused into a single HDR image. The data collection and HDR generation procedures are adopted from Stumpfel et al. (2004) and Inanici (2006; 2010), but the image calibration procedure presented here is novel.

The inability to capture the entire range of luminance values in sunny environments is referred as luminous overflow (Jakubiec et al., 2016). Even with a 22-stop exposure range that can corresponds to 7 logarithmic units, it may not be possible to account for the entire range of the sun disc. Therefore, the luminance values around the solar corona may be underestimated. Although the former practice suggests using the horizontal global illuminance measurement value (collected at the camera level) to calibrate the image (Inanici, 2010), this method does not address the underestimation of the luminance of the solar corona, and may yield to the overestimation of the luminance values for the rest of the sky. Instead, the direct horizontal irradiance and diffuse horizontal irradiance values are used here to calibrate the sun and the sky, respectively. The solar corona is extracted from the HDR images as a region (Radiance *mksource* program). This is determined by tracing rays to the sky image, where the region that has luminance values above 100,000 cd/m^2 is identified as the solar corona. The identified region is converted to one or more explicit light sources, where their contribution is matched to the direct horizontal irradiance value collected in situ. The rest of the image (i.e. sky) is scaled to match the diffuse horizontal irradiance value.

Table 1 illustrates the measured and simulated horizontal illuminance for each of the 4 sky type. The measurement based sky types (CIE_{BR}, Perez, and Image based) have the same direct and diffuse components. The CIE_{BR} and Perez skies are results of continuous mathematical functions; image based models incorporate actual atmospheric conditions and rapid changes around the boundaries of clouds. Therefore, the luminance compositions are different, but these 3 skies yield to approximately the same global, direct, and diffuse horizontal illuminances (with error margin < 2%). The CIE_{basic} option is not measurement based and it is modelled for given location, date, and time. This option yield to 30-40% differences in predicting the global horizontal illuminance values.

RESULTS AND DISCUSSION

Sidelit and toplit spaces are exposed to different portions of the sky. The simulations for the toplit and sidelit space are repeated for each selected instance. Both grid based illuminance calculations and image based luminance maps are performed (Table 2).

When generated or calibrated with diffuse and direct irradiance values, CIE_{BR}, Perez, and image based sky models yield to comparable results. The false color maps are comparable (the scale is 10-3000 lux in illuminance grids, and 100-10,000 cd/m^2 in luminance images). This is a significant finding as it demonstrates that a simple global horizontal measurement or a direct and diffuse irradiance data collected from a meteorological station can be as effective as the more laborious image based sky model. Although the luminance compositions of the sky models are different between the mathematical models and the image based model, the impact on the luminance and illuminance composition of the studied indoors were minimal among these 3 models. For comparing in-situ measurements with simulations, all three models yield satisfactory results.

Further analysis of the results (Table 3 and Figure 2) reveal that as expected, sky models for most cloudy skies is more consistent with each other. In clear skies, the size of solar region, and in partly cloudy skies, the luminance variations around the clouds impact the simulation results. For studied sidelit scenes, the luminance variations of the measurement based skies (CIE_{BR}, Perez, and image) produced linear fit equations with r-square values above 0.9. The largest error percentages are observed with June data in the toplit space. The variations of cloud cover around the zenith cause the discrepancy between mathematical and image based models.

The r-square values are consistently lower with CIE_{Basic} skies and root mean square error (RMSE) values are higher. CIE_{basic} skies should not be used to compare in-situ measurements with simulations. Unfortunately, it is a mistake that is observed too often among students and professionals. CIE_{basic} models provide generic sky conditions and they are useful to compare basic design alternatives.

It is important to emphasize that a separate calibration is warranted for the direct and diffuse components of the sky in image based models. With sunny skies, calibration with global illumination yields to errors. Figure 3 demonstrates simulation results with the two different calibration techniques and the difference between them.

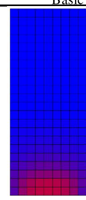
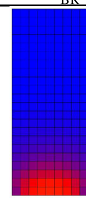
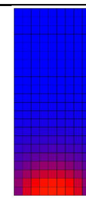
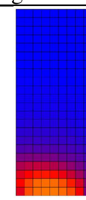
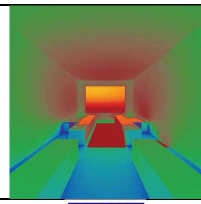
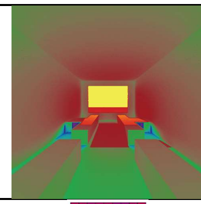
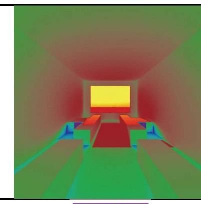
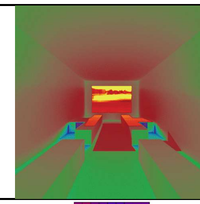
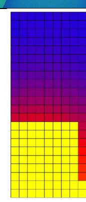
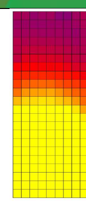
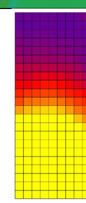
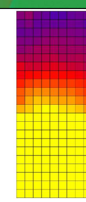
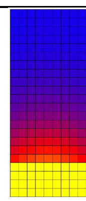
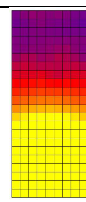
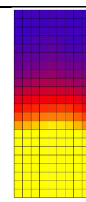
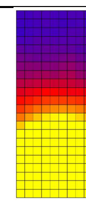
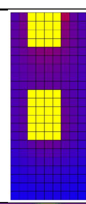
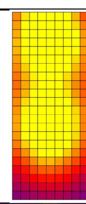
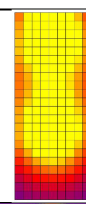
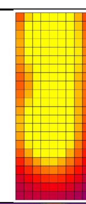
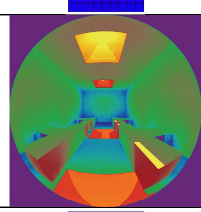
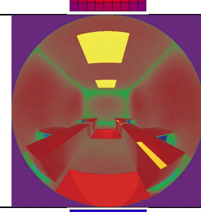
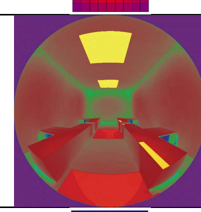
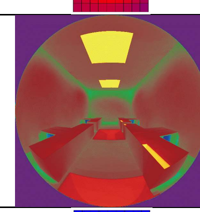
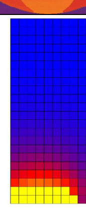
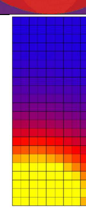
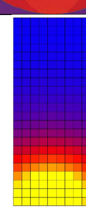
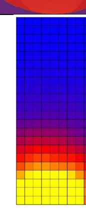
Table 3: Correlation between image based and mathematical based sky types in simulations

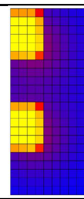
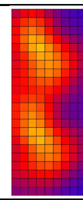
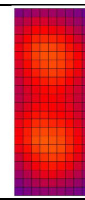
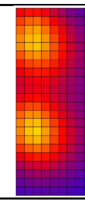
	Perez		CIE_{BR}		CIE_{Basic}	
sidelit	r^2	RSME	r^2	RSME	r^2	RSME
Jan 31	0.96	0.5	0.96	0.4	0.97	0.30
Feb 20	0.91	14.6	0.91	14.4	0.86	20.4
Apr 25	0.99	4	0.99	2.6	0.96	14.1
June22	0.98	1.1	0.99	1.1	0.78	4.1

toplit						
Apr 25	0.98	2.9	0.98	2.8	0.96	8.1

June22	0.70	1.1	0.67	1.9	0.24	7.3

Table 2: Simulation results

	CIE_{Basic}	CIE_{BR}	Perez	Image based sky
Jan 31, 11:00 South facing Window Illuminance (lux) 				
Feb 20, 12:00 South facing Window Luminance (cd/m^2)  10 10,000				
Feb 20, 12:00 South facing Window Illuminance (lux) 				
Apr 25, 12:00 Sidelit Illuminance (lux) 				
Apr 25, 12:00 Toplit Illuminance (lux) 				
June 22, 10:30 South facing Window Luminance (cd/m^2)  10 10,000				
June 22, 10:30 South facing Window Illuminance (lux) 				

June 22, 10:30 Toplit Illuminance (lux) 				

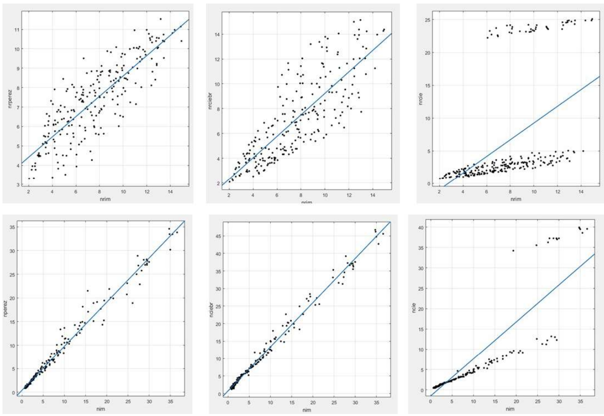


Figure 2 Comparison of image based model with a) Perez and b) CIE_{BR} and c) CIE_{Basic} models for June 22, 10:30 am: top row is the toplit and bottom row is the sidelit.

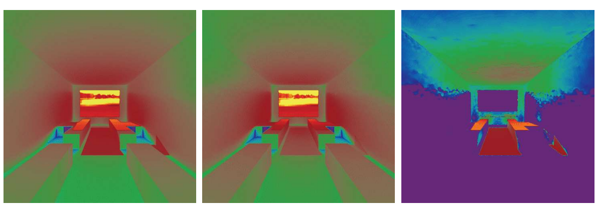
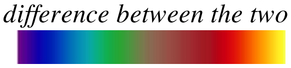


Figure 3. Comparison of image based skies calibrated with a) direct and diffuse irradiance; b) global irradiance; c) difference between the two techniques



1 10,000 cd/m2

CONCLUSION

This paper compares different sky models in lighting simulations with the goal of improving the utilization of right sky models in practice. The results suggest the following guidelines to improve the accuracy of daylight simulation techniques:

- CIE_{Basic} models are readily available to compare design alternatives, but they yield unacceptable errors when comparing simulation results with actual measurements.
- CIE_{BR}, Perez, and image based models provide sky luminance distributions derived from the direct and diffuse irradiance data, therefore, they account for the meteorological circumstances. Although there are some variations between the results, they are in general comparable.
- CIE_{BR} and Perez models are less laborious to obtain, so they can be successfully employed to compare real scenes and simulations. One particular caveat is the complex cloud compositions, where further accuracy is achieved with the image based sky models.
- Lack of adequate modelling of the context is major source of error in predicting the daylight availability and reflected glare. One of the advantages of utilizing image based models is that they include the surrounding buildings and vegetation.

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