Modeling Skylight Angular Luminance Distribution from Routine Irradiance Measurements

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Introduction

Skylight is a nonuniform extended light source. Its intensity and spatial distribution vary as a function of insolation conditions. In addition to direct sunlight, sky-luminance angular distribution is the necessary and sufficient information required for calculating daylight penetration into any properly described environment (e.g., a daylit space in a structure).[1,2] Because actual sky-luminance distribution data are available only in a handful of locations, it is essential to be able to estimate skylight distribution from routine measurements such as irradiance.[3]

In a recent study,[4] we evaluated six existing models[3-9] designed to account for changing light spatial distribution as a function of insolation conditions. The conclusions of the study were:

1. The best possible performance of any of these models is limited by the random nature of cloud brightness patterns superimposed on homogeneous luminance distribution patterns for any given insolation condition.
2. The best models tested[3,5] approached this ideal performance level; however, room for systematic improvement was noted.
3. The performance of empirically based models is satisfactory.[5]
4. The key to a model's performance is its ability to adequately parameterize insolation conditions.

In this paper we present a new model that is consistent with points 2, 3, and 4 above. The model is experimentally derived from a large pool of data (3 million data points) covering a wide range of insolation conditions, and relies on a parameterization of insolation conditions that has proven to be versatile and largely site-independent.[3] We address the random cloudiness issue in a separate paper.[10]

Methods

This model can be logically divided into three basic building blocks:

1. the model mathematical framework, an analytical expression relating luminance at any point in the sky to the selected input data
2. the input data and the parameters delineating insolation conditions
3. the functional form of the coefficients that relate the framework to the insolation condition parameters

The model's framework

We retained a mathematical expression that is a generalization of the CIE standard clear-sky formula.[11] This general expression includes five coefficients that can be adjusted to account for luminance distributions ranging from totally overcast to very clear. The relative luminance lv, defined as the ratio between the sky luminance at the considered point Lv and the luminance of an arbitrary reference point is given by:

$$lv = f(\zeta,\gamma) = [1 + a\ \exp(b/\cos\zeta)][1 + c\ \exp(d\gamma) + e\ \cos\gamma^2] \quad (1)$$

where ζ is the zenith angle of the considered point and γ is the angle between the considered point and the position of the sun. The coefficients a, b, c, d, and e are adjustable coefficients, functions of insolation conditions.

Lv may be obtained from lv via normalization to zenith luminance Lvz, e.g., modeled from Perez, et al.[3] More generally, we recommend that Lv be obtained after normalization of the modeled sky to diffuse illuminance Evd.[3]

The relative intensity and width of the circumsolar region, the sign and shape of the horizon-zenith gradient, and the relative importance of backscattering may be specified by adjusting the coefficients a, b, c, d, and e. The effect of each coefficient on the model's skylight distribution pattern is briefly described below. A more detailed description may be found in Perez, et al.[12]

Depending on the sign of coefficient a, the model will exhibit either a darkening ($a > 0$) or a brightening ($a < 0$) of the horizon region with respect to the zenith (corresponding respectively to overcast and clear-sky conditions), proportional to the absolute value of a. The brightness gradient near the horizon may be modulated by adjusting coefficient b. The value of coefficient c sets the relative intensity of the circumsolar brightening. Coefficient d accounts for the spatial extent of the circumsolar brightness region. Finally, coefficient e accounts for the relative intensity of backscattering (also known as antisun brightening).

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Model input and parameterization of insolation conditions

The model is designed to use hourly or more frequent global and direct irradiance to predict sky-luminance angular distribution. The model could also be used in a global-only input mode by generating hourly direct irradiance from global.[13]

The relative sky-luminance distribution is modeled using **Equation 1**. Direct and global irradiance are used to parameterize insolation conditions. This parameterization is identical to that reported in Perez, et al.[3] wherein insolation conditions are described as a three-dimensional space including the solar zenith angle Z, the sky's clearness ϵ, and the sky's brightness Δ. Note that this parameterization has proven to be largely site-independent for models concerned with sky light anisotropy.[3,14,15]

Functions relating coefficients to insolation

The five coefficients of the model are treated as functions of Δ, ϵ, and Z. The functions are derived via a nonlinear least square fitting of **Equation 1** to a large experimental database described below. The functions are structurally similar to that of the irradiance and daylight availability models described in Perez, et al.[3] That is, the functions are analytical in terms of Δ and Z and discrete in terms of ϵ. For each coefficient, a total of eight functions of Δ and Z corresponding to eight ϵ bins are derived. The functional forms are given in **Table 1**.

Experimental database

The experimental set of data includes more than 16,000 full-sky scans recorded in Berkeley, CA, be-

Table 1—Model coefficients

for sky clearness ranging from	to	a1	a2	a3	a4	b1	b2	b3	b4
1.000	1.065	1.3525	-0.2576	-0.2690	-1.4366	-0.7670	0.0007	1.2734	-0.1233
1.065	1.230	-1.2219	-0.7730	1.4148	1.1016	-0.2054	0.0367	-3.9128	0.9156
1.230	1.500	-1.1000	-0.2515	0.8952	0.0156	0.2782	-0.1812	-4.5000	1.1766
1.500	1.950	-0.5484	-0.6654	-0.2672	0.7117	0.7234	-0.6219	-5.6812	2.6297
1.950	2.800	-0.6000	-0.3566	-2.5000	2.3250	0.2937	0.0496	-5.6812	1.8415
2.800	4.500	-1.0156	-0.3670	1.0078	1.4051	0.2875	-0.5328	-3.8500	3.3750
4.500	6.200	-1.0000	0.0211	0.5025	-0.5119	-0.3000	0.1922	0.7023	-1.6317
6.200	—	-1.0500	0.0289	0.4260	0.3590	-0.3250	0.1156	0.7781	0.0025
		c1	c2	c3	c4	d1	d2	d3	d4
1.000	1.065	2.8000	0.6004	1.2375	1.0000*	1.8734	0.6297	0.9738	0.2809**
1.065	1.230	6.9750	0.1774	6.4477	-0.1239	-1.5798	-0.5081	-1.7812	0.1080
1.230	1.500	24.7219	-13.0812	-37.7000	34.8438	-5.0000	1.5218	3.9229	-2.6204
1.500	1.950	33.3389	-18.3000	-62.2500	52.0781	-3.5000	0.0016	1.1477	0.1062
1.950	2.800	21.0000	-4.7656	-21.5906	7.2492	-3.5000	-0.1554	1.4062	0.3988
2.800	4.500	14.0000	-0.9999	-7.1406	7.5469	-3.4000	-0.1078	-1.0750	1.5702
4.500	6.200	19.0000	-5.0000	1.2438	-1.9094	-4.0000	0.0250	0.3844	0.2656
6.200	—	31.0625	-14.5000	-46.1148	55.3750	-7.2312	0.4050	13.3500	0.6234
		e1	e2	e3	e4				
1.000	1.065	0.0356	-0.1246	-0.5718	0.9938				
1.065	1.230	0.2624	0.0672	-0.2190	-0.4285				
1.230	1.500	-0.0156	0.1597	0.4199	-0.5562				
1.500	1.950	0.4659	-0.3296	-0.0876	-0.0329				
1.950	2.800	0.0032	0.0766	-0.0656	-0.1294				
2.800	4.500	-0.0672	0.4016	0.3017	-0.4844				
4.500	6.200	1.0468	-0.3788	-2.4517	1.4656				
6.200	—	1.5000	-0.6426	1.8564	0.5636				

for x = a, b, c, d and e:

$$x = x_1 + x_2 Z + \Delta [x_3 + x_4 Z]$$

except for first sky clearness bin where

* $c = \exp[(\Delta (c_1 + c_2 Z))^{c_3}] - 1$

** $d = -\exp[\Delta (d_1 + d_2 Z)] + d_3 + \Delta d_4$

tween June 1985 and December 1986. The data include a wide range of insolation conditions from overcast to clear through intermediate skies.

Each full-sky scan consists of 186 luminance measurements, amounting to a total of almost 3 million data points. Measurements were performed using a multipurpose scanning photometer developed by Pacific Northwest Laboratory. This instrument is well suited to this application.[17] In addition to sky scans, we also have time-coincident measurements of direct illuminance. Measurements for the primary input to the model, global and direct irradiance, are not available directly. However, using direct illuminance and diffuse illuminance allows us to adequately parameterize insolation conditions via back-modeling the corresponding direct and global irradiance.[3]

Results

Model derivation

The coefficients derived via least-squares fitting of the model to the data are reported in **Table 1**. In its operational form the model first determines the coefficients a_i–e_i as a function of ϵ. The coefficients a, b, c, d, and e are then calculated based on Δ and Z as shown in **Table 1**. Relative sky luminance is derived using **Equation 1** and normalized to diffuse illuminance available as per Perez, et. al.[3] Typical values of the coefficients a, b, c, d, and e extracted from **Table 1** for each of the eight sky clearness bins at mid-range solar zenith angles have been plotted in **Figures 1–5**, respectively.

Coefficient a is positive for overcast conditions (first ϵ bin) but rapidly becomes negative for intermediate and clear conditions, indicating a displacement of the non-circumsolar brightening from the zenith to the horizon. The effect of coefficient a can be assessed by comparing the overcast and clear luminance profiles in **Figures 6** and **7**. In agreement with recent observations,[18] the dark overcast zenith brightening is found to be less significant than that suggested in the CIE standard overcast sky.[19]

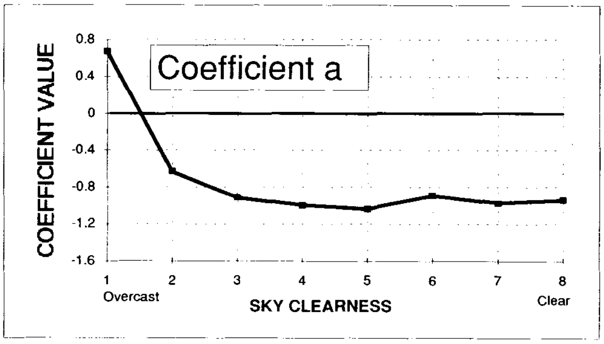

Figure 1—Variations of coefficient a with sky clearness ϵ obtained from Equation 6 **for Z = 45 degrees and Δ corresponding to the mean brightness value in each ϵ bin**

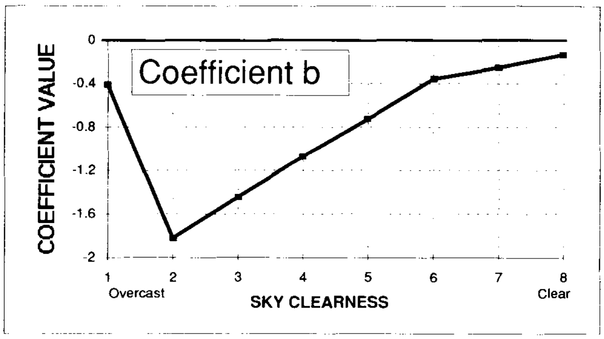

Figure 2—Same as Figure 1 **but coefficient b**

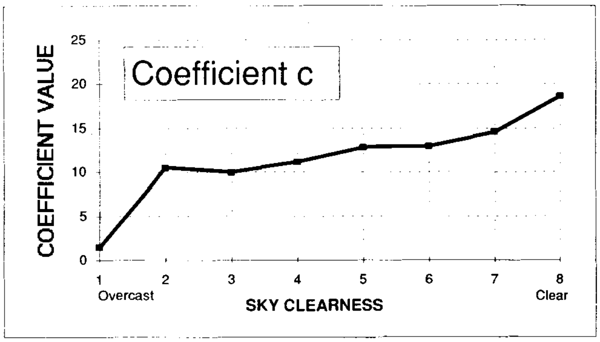

Figure 3—Same as Figure 1 **but coefficient c**

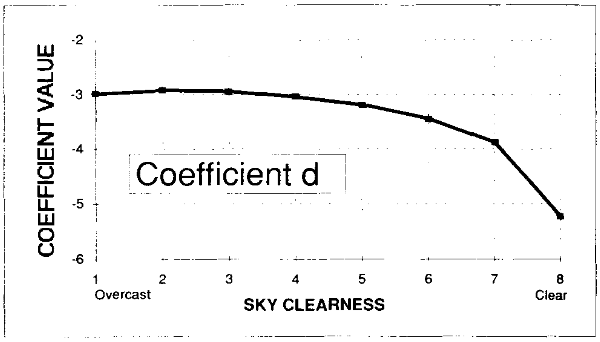

Figure 4—Same as Figure 1 **but coefficient d**

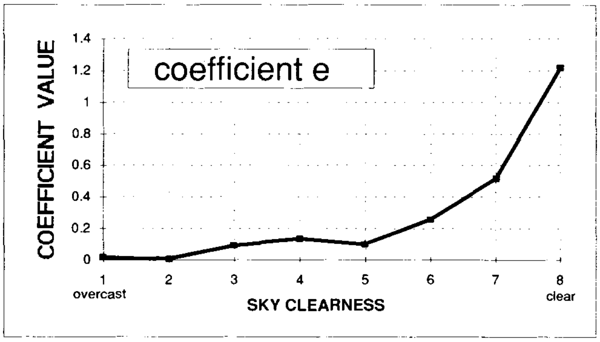

Figure 5—Same as Figure 1 **but coefficient e**

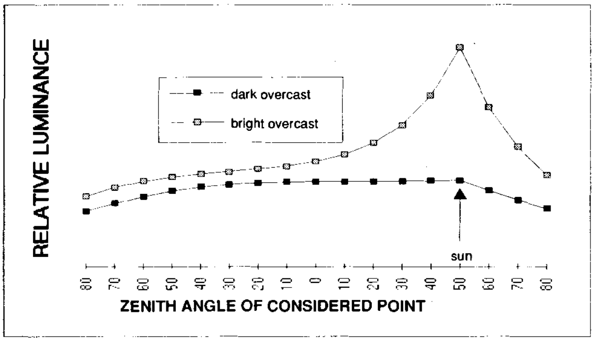

Figure 6—Modeled luminance in the plane of the sun for dark and bright overcast conditions

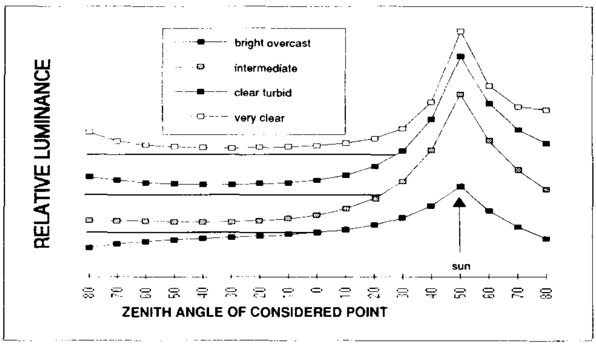

Figure 7—Modeled luminance in the plane of the sun for different levels of sky clearness

Coefficient b exhibits a gradual decrease in absolute value from the second ϵ bin (intermediate conditions) on. This indicates that the model goes from no noticeable horizon brightening for intermediate conditions to a well defined horizon band with a steep brightness gradient for clear conditions. This can be visualized as in **Figure 7** where luminance profiles corresponding to bright overcast (first ϵ bin, dark horizon), intermediate (third ϵ bin), turbid (sixth ϵ bin), and very clear conditions (eighth ϵ bin) have been plotted.

The circumsolar intensity coefficient c exhibits a marked increase from overcast to partly cloudy conditions and then gradually increases toward clear conditions. This effect can be visualized as in **Figure 6** where luminance profiles for bright and dark overcast skies are compared.

Coefficient d, which accounts for the width of the circumsolar brightness region, decreases exponentially with clearness. This indicates that the solar aureole is considerably narrower for clear skies than for turbid skies. It is interesting to note that the value of d $= -3$ found in the CIE clear-sky model appears to be an upper limit value for all conditions; however, the aureoles modeled here for clear conditions are substantially narrower than those of the CIE. Finally, the backscattering coefficient e increases exponentially with clearness for the three highest ϵ categories, as conditions tend toward a molecular (Rayleigh) atmosphere.

Model validation

The model is validated using the mean bias error (MBE) and root mean square error (RMSE) benchmarks computed after 3 million modeled and measured luminances are compared.

Table 2—Summary of model validation: Mean, MBE, and RMSE (in cd/m²)

ALL CONDITIONS (15929 scans)

	Entire Sky		Zenithal Region		Sun-facing Region		E/W-of-sun Region		N-of-sun Region	
Mean Luminance	4748		4294		8377		4003		3446	
	MBE	RMSE	MBE	RMSE	MBE	RMSE	MBE	RMSE	MBE	RMSE
ASRC-CIE	-75	2113	87	1920	-10	3776	-42	1396	-361	1250
Brunger	227	2312	207	2092	-489	4157	-268	1511	-333	1344
Perraudeau	26	2553	-250	2238	36	4097	111	1913	112	2147
Harrison	197	2363	283	2045	-1063	4324	-195	1522	109	1356
Matsuura	161	2443	267	2255	-1058	4451	-27	1489	-46	1426
Kittler	229	2520	461	2350	-1373	4536	-165	1552	-6	1552
Mean sky	0	1880	0	1768	1	3319	1	1264	0	1079
This Model	-12	1966	23	1846	-24	3469	-41	1320	22	1144

CLEAR SKY CONDITIONS (4803 scans)

	Entire Sky		Zenithal Region		Sun-facing Region		E/W-of-sun Region		N-of-sun Region	
Mean Luminance	3808		3040		7155		3199		2757	
	MBE	RMSE	MBE	RMSE	MBE	RMSE	MBE	RMSE	MBE	RMSE
ASRC-CIE	-101	1051	-23	1135	100	1736	-125	681	-310	713
Brunger	-275	1350	96	1072	-394	2442	-310	887	-453	910
Perraudeau	-340	1434	121	1032	393	2175	-579	1182	-965	1390
Harrison	-300	1334	261	1014	-664	2374	-441	1013	-224	726
Matsuura	-102	1051	-22	1135	95	1734	-125	681	-312	715
Kittler	-252	1163	450	1196	-394	1833	-383	849	-534	860
Mean sky	0	773	0	761	0	1307	0	543	0	472
This Model	-10	905	-18	897	5	1558	-103	587	177	585

BRIGHT OVERCAST CONDITIONS (685 scans)

	Enti Sky		Zenithal Region		Sun-facing Region		E/W-of-sun Region		N-of-sun Region	
Mean Luminance	12067		14238		18393		10244		7954	
	MBE	RMSE	MBE	RMSE	MBE	RMSE	MBE	RMSE	MBE	RMSE
ASRC-CIE	36	3952	193	4038	-999	7018	573	2474	-282	1981
Brunger	-26	4423	534	5009	582	7676	-553	2605	-43	2172
Perraudeau	161	6144	-1665	5872	-3412	9120	2736	4631	4829	5743
Harrison	57	4382	401	4404	-3195	7772	519	2607	1722	2666
Matsuura	-431	5877	1242	6021	-7319	10660	426	3077	2420	3558
Kittler	-365	5981	964	6085	-7379	10765	591	3176	2736	3829
Mean sky	0	3721	0	3960	2	6584	0	2212	0	1929
This Model	-38	3790	340	4027	-501	6662	-85	2304	110	1989

DARK OVERCAST CONDITIONS (789 scans)

	Entire Sky		Zenithal Region		Sun-facing Region		E/W-of-sun Region		N-of-sun Region	
Mean Luminance	1114		1313		1109		1055		1043	
	MBE	RMSE	MBE	RMSE	MBE	RMSE	MBE	RMSE	MBE	RMSE
ASRC-CIE	-59	554	108	402	-146	752	-88	523	-88	533
Brunger	-24	527	42	377	-87	717	-28	496	-25	507
Perraudeau	95	586	-180	438	243	773	139	555	148	574
Harrison	15	596	-45	457	356	888	-40	513	-122	545
Matsuura	-59	554	108	402	-146	752	-88	523	-88	533
Kittler	-59	555	109	403	-147	752	-88	523	-89	533
Mean sky	0	497	0	357	1	670	0	469	0	484
This Model	-1	521	-18	372	-41	706	23.5	493	2	504

All-sky error summaries are provided for the entire experimental data set and for three distinct sky conditions: 1. dark overcast conditions ($\epsilon = 1, \Delta < 0.1$); 2. bright overcast conditions ($\epsilon = 1, \Delta > 0.4$); and 3. clear conditions ($\epsilon > 6$). Error summaries are also provided for four regions in the sky vault relative to the sun's position: 1. a zenithal region including all points below 30 degrees zenith angle, 2. a sun-facing region including all points above 30 degrees zenith angle within 45 degrees of the sun's azimuth, 3. a north-of-sun region including all points above 30 degrees zenith angle that are more than 135 degrees from the sun's azimuth, and 4. an east- or west-of-sun region including all remaining points.

The performance of the model is compared to that of the six models that we had previously evaluated,[3,5-9] as well as to that of an ideal luminance model defined as the mean sky luminance found for each of 750 (Δ,ϵ,Z) insolation condition bins.[4]

The rules for model evaluation are identical to that spelled out in Perez, et al.[4] That is, all models are normalized to horizontal diffuse illuminance. All the models are independent of the test database except for the new model. However, this parameterization scheme has proven largely site-independent for related models.

Validation results are reported in **Table 2**. The performance of the new model approaches that of the ideal model for all conditions and orientations. We note a systematic gain over the two models (ASRC-CIE[4] and Brunger[5]) that featured the best performance in our preliminary evaluation.

The performance gain of the new model is most noticeable in terms of directional mean bias errors. In order to best gauge this systematic performance improvement, we defined a distortion index as the sum of the model absolute bias errors in each of four sky-vault regions described above: this index illustrates the ability of a model to generate prevailing skylight distribution patterns representative of observations. In **Figure 8**, we have plotted the distortion index found for each model for the entire database and for the three sets of insolation conditions of **Table 2**. Note that the indices have all been normalized.

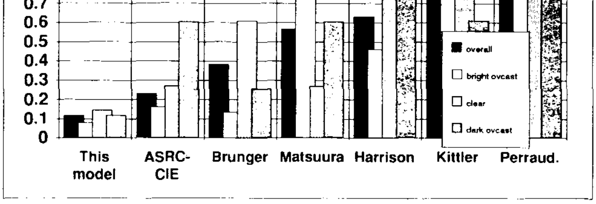

Figure 8—Relative distortion index of models

Conclusions

The model presented here combines a simple mathematical framework with a set of coefficients derived from a large, high-quality, experimental set of sky-scan data.

The coefficients act on the model's framework to account for the insolation-condition-dependent effects of forward scattering, backscattering, multiple scattering, and air mass on luminance distribution. Coefficients are treated as a function of three insolation condition parameters—solar elevation, sky clearness, and brightness—which may be derived from standard irradiance time series.

Validation results show that the performance of the model approaches the ideal level for this type of homogeneous model. That is, the model accounts for most mean anisotropic effects, but not random, one-of-a-kind, cloud effects. Modeling of random cloud effects is discussed in a separate paper. Of course, the validation performed here will have to be repeated on independent data. It is possible that the model may require adjustment to account for this database's site-specificity. The International Daylighting Measurement Program initiated by the CIE and WMO[20] should provide such a climatically diverse database.

Acknowledgments

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Discussion

The paper deals with one of the most important and exciting issues in daylighting. Energy efficiency in buildings depends on maximal use of natural light during daylight hours, among other factors. However, many of the so-called energy-efficient buildings failed to bring about the expected savings in energy. To a large extent this was caused by the lack of reliable design and calculation tools.

Skylight, not sunlight, is the major contributor to the daylight inside buildings. Still, without an accurate model for the luminance distribution of the sky, no reliable daylight calculations can be made. The existing accepted models describe only the extreme conditions of overcast and clear sky. In recent years attempts were made to develop a more representative model that will average all conditions from clear to partly cloudy to overcast.

The model presented in the paper is the latest, having been developed after analyzing most of the existing models, and is based on a large database. The new equation gives the relative sky-luminance distribution. It retains the basic mathematical expression of the CIE standard clear-sky model, which was developed by Richard Kittler. No doubt, the combination of sophisticated mathematical tools and the large database do produce a much more accurate and elaborate model for all sky conditions.

The paper should include, in my opinion, the definitions of the major factors, e.g., sky clearness and sky brightness, rather than referring non-expert readers to references.

The authors did whatever they could to validate their model, and believe it achieved almost the "ideal level" for the homogeneous sky. However, the database, large as it was, represented 18 months of measurements in one location. I strongly support what they say in their conclusion, that the model needs much more field validation by data from different periods of time and different locations.

It is appropriate that the authors compare in detail their model with other models, particularly with the model developed recently by Matsuura's CIE committee.

The authors should be praised and congratulated for their work, and I hope they will proceed with its validation and, most importantly, produce a design tool, readily applied by the average designer.

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The new model is based on a mathematical expression that is a generalization of the CIE standard sky formula by Richard Kittler with adjustments to account for effects such as circumsolar brightening, horizon brightening, or zenith brightening. The effect of cloud distributions is not included.

The paper can be regarded as a starting point to a continuous sky model representing real skies, but the influence of cloudiness requires some consideration as an intrinsic part of the modeling process rather than being addressed as a random happening. I have commented on two aspects introduced in this paper, namely the approach taken in the development of a sky model and the cloudiness problem.

Our sky-scanner data analysis in Sydney, Australia, is in its early stages, but a number of preliminary conclusions can be drawn that have relevance to this paper. First, it is evident from the results that the robustness of the CIE clear sky can be used as a temporary stopgap while other continuous sky models are being developed. Second, a new overcast sky including a solar component is required to replace the CIE overcast sky.

It has been found from the analysis of clear-sky data recorded by the Krochmann sky scanner in Sydney that both CIE clear-sky models (high and low turbidity) are extremely flexible, being by far the best fit to clear skies in Sydney up to a cloud cover of 4 octas. However, their ability to accurately predict diffuse illuminance drops off to approximately ± 20 percent, generally underestimating values. The CIE clear sky with high turbidity appears from the data to be the more suitable clear-sky model for Sydney.

As in Perez's research on sky models, no single model we have evaluated using the sky scanner (i.e., the CIE overcast, overcast with a one-to-four ratio of zenith to horizon, BRE average, Harrison clear, and Harrison overcast) appears to satisfy partly cloudy sky (3–5-octa) distributions. In the overcast sky, it is evident that there is an increase in luminance in the sector toward the sun in azimuth and a relative decrease away from the solar position. As mentioned herein, dark overcast zenith brightening is found to be less significant than that suggested by the CIE standard overcast. The influence of the solar position in an overcast sky can be seen in **Figure 7**.

The approach that Perez, et al, have used to determine a sky-modeling base to portray the effects of circumsolar, zenith, and horizon brightening, without random cloud effects (i.e., the CIE clear-sky formula) is a logical starting point in developing a continuous sky model. However, further investigation and validation is required as the model is site-dependent, being derived from luminance and direct illuminance data measured in San Francisco, CA.

It should be noted that the sky model put forward by Perez, et al. accounts for mean anisotropic effects only and not random one-of-a-kind cloud effects that are discussed in another paper. I assume here that *one-of-a-kind* refers to a specific cloud type. However, the separation of one of the most important functional parameters of daylight availability, i.e., the distribution of cloud amount and type, from the intrinsic sky model, is questionable. Cloud distributions are continuous as portrayed by our sky camera coincident with 15-min luminance scans, and their influence on the daylighting of interiors varies with different orientations. Hence, cloudiness distributions should be included in any basic approach to sky modeling rather than investigated as a separate issue.

Our data analysis in Australia has highlighted the importance of the amount of cloud cover upon daylight variables. It is not a simple variable for any model formulation, as there are problems with the accuracy of cloud cover estimation. Estimation variability can be high even with experienced observers. However, this problem can be solved with fisheye photographs coincident with the sky scans and the use of blue and red filters in the sky scanner to provide more accurate results. The spread of values in our sampled luminance data was wide; therefore, an accurate assessment requires in the order of at least 100 sample points.

It was concluded in our current research that although lower solar altitudes tend to produce lower average sky luminances for a particular cloud cover, it is not necessarily true that higher solar altitudes produce higher average luminances. Any assumption that solar altitude is a determining factor in sky modeling therefore has to be questioned. It was also found that the averaged quantity, mean RB ratio, is inconclusive as an indicator of total cloud cover although there does appear to be some identifiable clustering when there is normalization to average sky luminance.

The development of a new model by Perez needs to include cloudiness or turbidity as functional variables in order to address the problem of their important influence on daylight availability. More detailed analysis of actual cloud amount by full-field sky images needs to be carried out, as well as an analysis of red- or blue-filtered scan data to determine the degree of cloudiness influence on continuous luminance distributions before any empirical model can be adopted.

As mentioned by Perez, the International Daylighting Measurement Program will provide data to establish cloudiness effects in more detail.

N. Ruck

Authors' response

To E. Ne'eman and N. Ruck

We agree with the need for extended validation of the model. We intend to make use of data recorded under the auspices of the CIE'S International Delighting Measurement Program for this purpose.

Concerning the discussion on cloudiness, we do not treat the cloud issue completely independently from the model described here, but simply recognize the fact that sky luminance distribution contains both deterministic (predictable) features, such as horizon zenith gradients and circumsolar effects, and non-deterministic features, such as the position, size, and pattern of a given cloud formation at a given point in time; each being unique or "one-of-a-kind." This paper deals with the deterministic aspect of sky luminance while our following paper, which the reviewers had probably not read, deals with the modeling of non-deterministic cloud effects. Non-deterministic or "random" cloud effects are modeled as luminance departure (>0 or <0) from the deterministic (homogeneous) model presented here. We refer to these luminance departures as random luminance, although this term may not be the most appropriate. Indeed, although cloud effects are one-of-a-kind or random, some of their features may be predictable when properly parameterized as a function of insolation conditions. These features, which include the intensity distribution of non-deterministic luminance and its spatial auto-correlation, are the features that will inherently account for cloud type in a model.

One comment by Ruck deals with the need to incorporate turbidity and cloud cover as additional input to the sky model. Turbidity is inherently included in the model since direct irradiance and the sun's elevation are two inputs to our model. Linke turbidity is a simple function of direct irradiance and the sun's elevation.

We made a conscious decision not to use cloud cover as input for two reasons. This model is designed to exploit irradiance data as input. Irradiance is among the most widely measured radiative quantities in the world. Recent developments in rugged automatic instrumentation will make that input even more accessible in the future. Cloud cover is generally observed by a human observer and is consequently subject to fluctuations and bias (from site to site and observer to observer). Measured cloud cover is not a routinely accessible quantity and would be considerably more expensive to measure than irradiance.