Qualitative and quantitative assessment of outdoor daylight on vertical surfaces for six climate specific Indian cities

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Abstract: This article deals with experimental validation of solar illuminance model for vertical plane surfaces against measured solar global illuminance at New Delhi. The paper also deals with computation of solar illuminance (daylight), both quantitatively and qualitatively, on four cardinal vertical surfaces at six Indian stations. The stations identified for the study are: New Delhi, Jodhpur, Pune, Kolkata, Shillong and Leh. Quantitative analysis of daily average solar illuminance shows that most of the stations under study receive maximum illuminance on north, east and west surfaces, during summer months of April–July, whereas the south surface receives maximum illuminance during winter months of November–February. Higher range of daily average solar illuminance on four vertical surfaces is evaluated as follows: 45–55 klx on south surface, 20–35 klx on west surface (all the stations except Pune), 20–30 klx on east (Pune) and 14–15 klx on north surface. Qualitative analysis shows that for the global illuminance in the range of 20–40 klx, for four vertical surfaces, the percentage of annual day time is: 3–8% for north surface, 25–30% for south surface, 20–30% for west surface and 20–25% for east surface.

Subjects: Clean Technologies, Environmental, Renewable Energy

Keywords: sky diffuse illuminance, daylight on vertical surface, cumulative frequency of solar illuminance

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PUBLIC INTEREST STATEMENT
Qualitative and quantitative assessment of daylight availability on vertical surfaces provides crucial inputs for the building designer so that daylight could be exploited to the full potential in the building. Daylight data for vertical surfaces is required for optimising the size and glazing material for the window, so as to conserve lighting energy in a building. Solar radiation data are available for most of the cities around the world but daylight (solar illuminance) data are hardly available. There is a need to generate daylight data from solar radiation data, through empirical or semi-empirical models, as daylight measurement is a very costly affair. This study provides inputs to the Strategists and policy-makers, at regional and national level of India, in benchmarking the energy conservation potential of lighting in the building sector.
1. Introduction
Lighting is the second largest consumer of energy in building sector. It accounts for 20% of total electric energy consumed in India (World Bank Report, 2008). Daylight is one of the most preferred options, and should be exploited to the fullest extent in order to conserve artificial lighting energy in buildings. Recent advent and popularity of advanced daylight systems such as light pipes, light guides, energy efficient windows and glazed wall, have created a demand for daylight data for vertical surfaces, so that daylight systems could be optimised for the fullest exploitation of the daylight.

Qualitative and quantitative assessment of daylight on vertical surfaces finds prime significance due to the fact that daylight could be exploited substantially through the vertical surfaces, mounted with window and glazed wall of a building. Daylight data are useful for the estimation of energy conservation potential of the daylight in lighting sector of the buildings for local, regional and even at national level. There is a need of outdoor daylight data, for different climatic conditions, which provides inputs for the design, simulation and optimisation of the glazing area, so that use of daylight could be maximised and hence, minimise the use of artificial light in a building.

International Commission on Illumination (CIE) model, Perez et al. models and Igawa model are some of the widely used empirical/semi-empirical models to generate daylight data for the stations, where measured daylight data are hardly available. Perez, Seals, and Michalsky (1993) developed and evaluated an all-weather model for instantaneous sky luminance, and evaluated six other models from recorded sky scans. Frame work of the model is based on CIE standard clear sky general formula. Li and Lam (2003) formulated a sky luminance model from the measurements at Hong Kong. Their model performed better than Perez et al. model. Li, Lam, Cheung, and Tang (2008) developed and validated a luminous efficacy model for sky diffuse illuminance, on four vertical surfaces under 15 CIE standard skies, using measured illuminance and irradiance data for Hong Kong. De Rosa, Ferraro, Kaliakatsos, and Marinelli (2008), Robledo and Soler (2003), developed luminous efficacy models for diffuse illuminance and global illuminance, respectively, for vertical surfaces. Their models were validated and found to give a better performance as compared to existing models. Ferraro, Mele, and Marinelli (2012) assessed the Perez et al. model, Igawa model and CIE model against one year measured sky luminance data for Osaka (Japan), and for Arcavacata (Italy). Ferraro found that Igawa model provides accurate results when used for the evaluation of absolute sky diffuse luminance, whereas Perez et al., all-weather models are better for the evaluation of relative sky diffuse luminance.

We find little literature concerned to annual daylight assessment on vertical plane surfaces for Indian stations representing all the climatic zones. The novelty in this research is the use of weather data for typical meteorological year (TMY) for generating solar illuminance data. TMY weather data reflects most prevailing weather data for the previous 20 years. And use of the empirical and semi-empirical models for solar illuminance, followed by the experimental validation of these models, by the authors.

2. Theoretical basis and methodology
2.1. Solar illuminance model for vertical surface
Total solar illuminance on a vertical surface is the sum of beam illuminance, sky diffuse illuminance and ground reflected illuminance, as illustrated in Figure 1. Solar illuminance model for vertical surface consists of the parametric model for sky diffuse illuminance, mathematical models for ground reflected illuminance and beam illuminance. Sky diffuse illuminance is evaluated using Perez et al. (1993) all-weather model while, ground reflected illuminance and beam illuminance are evaluated using the relevant equations, used for ground reflected irradiance and beam irradiance on a vertical surface. Solar illuminance on the horizontal surface required by these models is evaluated using Perez et al., luminous efficacy model.
2.1.1. Perez et al. luminous efficacy model
Luminous efficacy of solar irradiance is defined as the ratio of solar illuminance on an unobstructed horizontal surface to the corresponding solar irradiance (Kittler, Kocifaj, & Darula, 2012). Perez, Ineichen, Seals, Michalsky, and Stewart (1990) formulated luminous efficacy models from extensive measurements of both solar illuminance and solar irradiance on a horizontal surface. Various parameters like solar zenith angle, sky clearness, sky brightness and their effect on luminous efficacy are taken into account by the model coefficients, derived through empirical analysis. Solar geometrical angles required for the models have been referred from Duffie and Beckman (2006).

Solar global illuminance on horizontal surface ($L_{gh}$), is given as (Perez et al., 1990)

$$L_{gh} = \frac{I_{gh}}{a' + b'w + c' \cos(\theta_z) + d' \log(\Delta)}$$  \hspace{1cm} (1)

where $I_{gh}$ is the solar global irradiance (W/m²); $a'$, $b'$, $c'$ and $d'$ are model coefficients, which are selected based on the value of sky clearness and sky ratio (Perez et al., 1990); $w$ is the atmospheric precipitable water content (cm); $\theta_z$ is the solar zenith angle (radian); and $\Delta$ is the sky brightness.

Sky brightness, $\Delta = \frac{I_{dh} \cdot m}{I_o}$ \hspace{1cm} (2)

where $I_{dh}$ is the solar diffuse irradiance (W/m²); $I_o$ is the solar extraterrestrial irradiance (W/m²); $m$ is the optical air mass at local atmospheric pressure (Kasten & Young, 1989) and the same is given as

$$m = \frac{m_o \cdot P}{1013.25}$$  \hspace{1cm} (3)

where $m_o$ is the optical air mass at atmospheric pressure at average sea level (Kasten & Young, 1989) given as

$$m_o = \left[ \sin \alpha_s + 0.50572 (\alpha_s + 6.07995)^{1.6364} \right]^{-1}$$  \hspace{1cm} (4)

where $\alpha$ is the solar altitude (radian); $P$ is the local atmospheric pressure (mbar) (Lunde, 1980), is given as

$$P = 1013.25 \cdot \exp (-0.0001184 \cdot h)$$  \hspace{1cm} (5)

where $h$ is the height of the station above the average sea level, 216 m for New Delhi.
Sky Clearness, 
\[ \epsilon = \frac{I_{dn} + I_{bn}}{I_{dn}} + 1.041 \cdot \theta^3_z \]  
where \( I_{bn} \) is the solar normal beam irradiance (W/m²).

Sky Ratio, 
\[ SR = \frac{I_{dn}}{I_{gh}} \]  
Solar diffuse illuminance on horizontal surface (\( L_{dh} \)) is given as
\[ L_{dh} = I_{dh} \left[ a'' + b''w + c'' \cos(\theta_z) + d'' \log(\Delta) \right] \]  
where \( a'', b'', c'' \) and \( d'' \) are the model coefficients which depend on sky ratio and sky clearness (Perez et al., 1990). Readers are suggested to refer Perez et al. (1990, 1993) and Patil, Garg, and Kaushik (2013) for details of model coefficients, available in tabular form.

2.1.2. Perez et al. all-weather model
Perez et al. (1993) developed an all-weather model for relative sky luminance of a sky segment. Model is a generalisation of CIE standard clear sky formula. Luminance distribution, due to different sky conditions (clear sky to overcast sky), is obtained by adjusting the five critical coefficients of the model. Figure 2 shows the geometrical angles related to the sky segment and the sun position in sky hemisphere. Relative luminance of a sky element \( l_{ij} \), in terms of zenith angle of sky segment \( \theta \), solar zenith angle \( \theta_z \) and angle between sky segment and sun position \( \xi \), is given as
\[ l_{ij}(\theta, \xi) = \frac{f(\theta, \xi)}{f(0, \theta_z)} = \frac{1 + a_i \cdot \exp \left( \frac{b_i}{\cos \theta} \right)}{\left[ 1 + a_i \cdot \exp (b_i) \right]} \times \frac{1 + c_i \cdot \exp (d_i \cdot \xi) + e_i \cdot \cos^2 \xi}{\left[ 1 + a_i \cdot \exp (d_i) \right]} \]
where \( a_i, b_i, c_i, d_i \) and \( e_i \) are the coefficients which are function of solar zenith angle, sky clearness and sky brightness. These are evaluated from model coefficients evaluated from empirical study which are represented by: \( a_i, b_i, c_i, d_i, e_i \) (\( j = 1 \) to \( 4 \), \( i \) (sky category) = 1 to 8) available in the tabular form, for eight categories of the sky conditions [2].
\[ a_i = a_{1,i} + a_{2,i} \cdot \theta_z + \Delta(a_{3,i} + a_{4,i} \cdot \theta_z) \]  \hspace{1cm} (10)

where \( b, c, d \) and \( e \) are evaluated similarly as that of Equation 10, with exception for \( c_1 \) and \( d_1 \) which are evaluated by equations 11 and 12

\[ c_1 = \exp \left[ \frac{\Delta(c_{1,1} + c_{2,1} \cdot \theta_z)}{c_1} \right] - 1 \]  \hspace{1cm} (11)

\[ d_1 = -\exp \left[ \Delta(d_{1,1} + d_{2,1} \cdot \theta_z) \right] + d_{3,1} + \Delta d_{4,1} \]  \hspace{1cm} (12)

From Figure 2 relation between \( \xi, \theta \) and \( \theta_z \) can be derived as

\[ \cos \xi = \cos \theta_z \cdot \cos \theta + \sin \theta_z \cdot \sin \theta \cdot \cos(\gamma - \gamma_z) \]  \hspace{1cm} (13)

\[ \theta = \frac{\pi}{2} - \alpha \]

Relative sky luminance (Equation 9) is first expressed in terms of altitude \( (\alpha) \) and azimuth angle \( (\gamma) \), and resulting equation is then substituted in Equation 14 to obtain the relative sky diffuse luminance \( (l_{rv}) \) on vertical plane surface.

\[ l_{rv} = \int_0^{\pi/2} \int_0^{\pi/2} l_r(\alpha, \gamma) \cdot \cos^2 \alpha \cdot \cos(\gamma - \gamma_{sur}) \, d\alpha \, d\gamma \]  \hspace{1cm} (14)

where \( \gamma_{sur} \) is the surface azimuth angle of vertical plane surface.

Relative sky diffuse illuminance on horizontal surface \( (l_{rh}) \) can be evaluated by equation

\[ l_{rh} = \int_0^{2\pi} \int_0^{\pi/2} l_r(\alpha, \gamma) \cdot \cos \alpha \cdot \sin \alpha \, d\alpha \, d\gamma \]  \hspace{1cm} (15)

Analytical solution of Equations 14 and 15 is difficult; hence numerical method is used and the same is given by Equations 16 and 17.

For horizontal surface,

\[ l_{rh} = \sum_{i=1}^{145} l_r(\alpha, \gamma) \cdot \cos \alpha \cdot \sin \alpha \cdot \Delta \alpha \cdot \Delta \gamma \]  \hspace{1cm} (16)

For east and west vertical surface,

\[ l_{rv} = \sum_{i=1}^{65} l_r(\alpha, \gamma) \cdot \cos^2 \alpha \cdot \cos(\gamma - \gamma_{sur}) \Delta \alpha \Delta \gamma \]  \hspace{1cm} (17)

For north and south vertical surface,

\[ l_{rv} = \sum_{i=1}^{69} l_r(\alpha, \gamma) \cdot \cos^2 \alpha \cdot \cos(\gamma - \gamma_{sur}) \Delta \alpha \Delta \gamma \]  \hspace{1cm} (18)

where \( i \) is the number of sky elements under consideration. There are 145 sky segments visible to horizontal surface as shown in Figure 3.

Absolute sky diffuse illuminance is evaluated from relative sky diffuse luminance using normalisation ratio. The normalisation Ratio (NR) is defined as the ratio of absolute sky diffuse illuminance to the relative sky luminance on a horizontal surface.
Normalisation Ratio (NR)

\[ NR = \frac{L_{dh}}{I_h} \]

where \( L_{dh} \) is either measured or evaluated using Perez luminous efficacy model given by Equation 8 Patil et al. (2013).

Absolute sky diffuse illuminance on vertical surface \( (L_v) \) is given as

\[ L_v = NR \times I_{rv} \]  

(19)

Beam illuminance on vertical surface \( (L_{bv}) \) is given as

\[ L_{bv} = \frac{(L_{gh} - L_{dh}) \cdot \cos \theta_z}{\cos \theta_z} \]  

(20)

where \( L_{gh} \) is measured or calculated using Perez et al., luminous efficacy model; \( \theta_z \) is solar incident angle on vertical surface (radian).

Ground reflected illuminance is given as

\[ L_{gr} = \frac{L_{gh} \times \rho}{2} \]  

(21)

where \( \rho \) is ground reflectivity (assumed to be .2 for urban area).
Total illuminance ($L_{tv}$) on vertical surface is given as

$$L_{tv} = L_v + L_{gr} + L_{bv}$$  \hspace{1cm} (22)

Figure 3 shows the projection of sky hemisphere on the horizontal plane. Sky hemisphere is divided into 145 segments. Each sky segment is identified by its altitude ($\alpha$) and azimuth ($\gamma$). Initially, the location of measurement is inspected for its exposure to sky hemisphere. Any sky segment, invisible for the instrument due to the obstruction posed by surrounding buildings, walls, vegetation, etc., is identified and marked by respective altitude and azimuth of sky segment, using the protractor (Figure 4). Obstructed sky segments are shaded as illustrated in Figure 3 and these sky segments are excluded from the evaluation of sky diffuse illuminance.

3. Experimental set-up

Initially, solar cardinal directions (north, south, east and west) at the location of measurement are marked using a pole shadow method. Further, the location is investigated for its exposure to sky hemisphere using the protractor as shown in Figure 4. Experimental set-up consists of a pyranometer (Kipp & Zonen make) to measure solar global irradiance and a photo sensor (LICOR make) to measure solar global illuminance on the vertical surface. Specifications of these two instruments are given in Table 1. Both the sensors are mounted on either side of the vertical surface of the wooden stand, as shown in Figure 5. Wooden stand can be turned about vertical axis manually so as to face the sensors towards cardinal directions for the measurement purpose.

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Table 1. Specifications of instruments

| Sl. No. | Instrument     | Specifications                      |
|---------|----------------|-------------------------------------|
| 1       | Pyranometer    | Make: KIPP and ZONEN, Holland       |
|         |                | Model: CM11,                        |
|         |                | Sensitivity: $5.03 \times 10^{-6}$ W/m², Linearity: ±.5% |
| 2       | Photometer     | Make: Li-COR, USA,                  |
|         |                | Accuracy: ±.4%, Range: 0–199 klx, Linearity: ±.05% |
4. Results and discussion

4.1. Indian climatic zones

Indian climates are highly diverse in nature and are classified, on the basis of ambient temperature and humidity (Bansal & Minke, 1995), into six climatic zones namely Hot and dry, Warm and humid, Composite, Moderate, Cold and cloudy, and Cold and sunny as shown in Figure 6. The main features of these climatic zones, as reported by Bansal and Minke (1995), are as follows:

4.1.1. Hot and dry climate
This climatic zone has flat with sandy ground, it receives high solar radiation in the range, 800–950 W/m². In summer, ambient temperature reaches to 40–45°C and in winter, maximum temperature reaches to 20–30°C. Relative humidity (RH) is usually in the lower range of 25–40% due to low vegetation and few surface water bodies.

4.1.2. Warm humid climate
This climatic zone constitutes mainly coastal part of India. Cloudy sky, high summer temperatures (30–35°C), high winter temperature (25–30°C) and high humidity (70–90% throughout the year) are the main features of this climate.

4.1.3. Composite climate
It consists of central part India, variable landscape and seasonal vegetation are the features of this climate. Solar intensity is very high in summer, low intensity in monsoon. Day time temperature reaches to 32–43°C during day and 27–32°C during night. In winter, ambient temperatures are in the range of 10–25°C during day time and 4–10°C during night time. RH is about 20–25% in dry period and 55–95% in wet period. Sky is overcast in monsoon, whereas it is clear in winter and hazy in summer.

4.1.4. Moderate climate
This climate is neither hot nor cool; it consists of hilly and high plateau regions. Abundant vegetation, uniform radiation, lower ambient temperatures are the outstanding features of this climate. In summer, highest temperature is in the range of 30–34°C. RH levels are in the range of 20–55% during winter and summer, whereas in monsoon it is 55–90%.

4.1.5. Cold and cloudy
This climate covers northern part of India; situated in high altitude with abundant vegetation even in summer season. Solar irradiance is low in winter with high percentages of diffuse component.

Figure 5. Measurement set-up for solar illuminance and solar irradiance on vertical surface.
Maximum ambient temperature is in the range of 20–30°C in summer while in winter, it is extremely low (4–8°C) during day time. RH is in the high range of 70–80%. Sky is overcast for most part of the year except summer.

4.1.6. Cold and sunny
This climate mainly exists in the region, Leh and Ladakh of northern India. Little vegetation, cold desert, intense beam radiation are the main features of this zone. In summer, temperature reaches to 17–24°C during day and it is 4–11°C during night; RH is in lower range of 10–50%. Sky is fairly clear throughout the year.
Six prominent stations, one from each climatic zone, selected for the study are: New Delhi (28.63°N, 77.2°E, 216 m) for composite climate, Jodhpur (26.29°N, 73.03°E, 231 m) for Hot and dry climate, Pune (18.52°N, 73.85°E, 560 m) for moderate climate, Kolkata (22.57°N, 88.37°E, 9 m) for warm and humid climate, Shillong (25.57°N, 91.88°E, 1525 m) for cold and cloudy climate and Leh (34.17°N, 77.58°E, 3500 m) for cold and sunny climate.

4.2. Experimental validation of solar illuminance model

Solar global irradiance and solar global illuminance on vertical surfaces were measured for every half an hour from morning 7.30 am to evening 5.30 pm. Measurements were carried out for 12 days, during March and April months of the year 2012, on rooftop of the building, Centre for Energy Studies, IIT Delhi. Solar global illuminance model for vertical surfaces was assessed for its performance by statistical parameters such as mean bias error (MBE), root mean square error (RMSE), relative error (RE) and Coefficient of Determination ($R^2$) (Muneer, 2004).

Table 2 shows MBE and RMSE values of solar illuminance model for four vertical surfaces. It is observed that solar illuminance model underestimates the actual illuminance on north surface, whereas it overestimates the solar illuminance on other three surfaces. South surface shows lowest MBE (0.30%), followed by east surface (3.87%), west surface (7.89%) and north surface (−8.65%). RMSE values show decreasing trends from 19.01 to 2.68 for north, south, east and west surfaces accordingly.

The REs of the model derived results for four vertical surfaces are presented in Table 3. Solar illuminance model for vertical surfaces performed better for east surface with 70% of results for this surface fall within ±10% RE. For south surface, 70% of results fall within ±15% of RE and overall analysis shows 80–90% of results derived by the model for all the four surfaces fall in the range of ±25% of RE.

Table 7 shows the relation between measured global illuminance and model derived global illuminance. The value of Coefficient of Determination ($R^2$) represents how well the predicted data correlate with measured data. It is observed that for all the four vertical surfaces, illuminance model was performed satisfactorily, as the model derived illuminance varies linearly with measured illuminance. $R^2$ value is more than .9 for east surface, west surface and south surface, and it is about .8 for north surface. The $R^2$ value higher than .9 indicates a good agreement between models derived

| Surfaces | MBE (%) | RMSE (%) |
|----------|---------|----------|
| North    | −8.65   | 19.01    |
| South    | 0.30    | 16.00    |
| East     | 3.87    | 12.99    |
| West     | 7.89    | 2.68     |

| Range of relative error (%) | Percentage of results for vertical surfaces | North | South | East | West |
|-----------------------------|---------------------------------------------|-------|-------|------|------|
| ±05                         |                                             | 18    | 28    | 38   | 28   |
| ±10                         |                                             | 41    | 54    | 69   | 47   |
| ±15                         |                                             | 56    | 71    | 79   | 67   |
| ±20                         |                                             | 71    | 80    | 89   | 84   |
| ±25                         |                                             | 82    | 88    | 92   | 91   |

Table 2. MBE and RMSE of solar illuminance model

Table 3. Validation of solar illuminance model based on RE
illuminance and measured illuminance. North surface doesn't receive direct illuminance, and direct illuminance can be evaluated more precisely as compare to diffuse illuminance. Hence, $R^2$ value is slightly smaller for the north surface.

Figure 3 shows the projection of sky hemisphere on the horizontal plane. Sky hemisphere is divided into 145 segments according to international standard practice, and each sky segment is specified by its altitude ($\alpha$) and azimuth ($\gamma$). Initially, the location of measurement is inspected for its exposure to sky hemisphere. The sky segments, invisible to the instrument due to the obstruction caused by the surrounding buildings, terrain and vegetation etc., are identified, and obstructing sky segments are marked by their respective altitude and azimuth angle, using the protractor (Figure 4). Obstructing sky segments are shown with shaded colour as shown in Figure 3, and shaded sky segments are excluded from the evaluation of sky diffuse illuminance.

4.3. Quantitative assessment of daylight on vertical surfaces
Hourly values of solar irradiance, solar geometric angles and other weather data for a TMY, required in the solar illuminance model, were generated through simulation in the TRANSYS software. Solar illuminance model is constituted by three models; first model is for sky diffuse illuminance, computed using Perez et al. all-weather model, second is for ground reflected illuminance and third is for beam illuminance. Solar illuminance on the horizontal surface, required for the evaluation of ground reflected and beam illuminance on vertical surface, was evaluated using Perez et al. model for the luminous efficacy of solar irradiance.

Daily average solar illuminance was computed from monthly average hourly global as well as diffuse illuminance on vertical surface for 12 months of a TMY. The study was carried out for all the six stations, and for four vertical surfaces, the results are presented in Figures 8–15.

4.3.1. Daily average solar illuminance on the north surface
Daily average solar global illuminance on the north surface for all the stations is shown in Figure 8. It is observed that for most of the stations, highest illuminance occurs during summer month of June, except for New Delhi station, where it is in the month of July. Peak values are found to be in the range of 14–15 klx for New Delhi, Jodhpur, Pune, and Kolkata, whereas for Shillong and Leh stations, it is in the range of 10–12 klx during July, August and September. A decreasing trend of illuminance
Figure 8. Daily average solar global illuminance on north surface.

Figure 9. Daily average solar diffuse illuminance on north surface.

Figure 10. Daily average solar global illuminance on south surface.

Figure 11. Daily average diffuse illuminance on south surface.
Figure 12. Daily average solar global illuminance on east surface.

Figure 13. Daily average diffuse illuminance on east surface.

Figure 14. Daily average solar global illuminance on west surface.

Figure 15. Daily average diffuse illuminance on west surface.
is seen in monsoon season. For most of the stations, daily average solar illuminance follows decreasing trend in monsoon and winter season, and minimum level is found in the range of 6–8 klx in the months of December and January. Daily average solar diffuse illuminance on north surface, as shown in Figure 9, follows almost same trends and levels of daily average global illuminance on this surface, as the north surface at all the stations receive only diffuse illuminance throughout the year.

4.3.2. Daily average illuminance on the south surface
South surface attracts higher attention for energy conservation through daylighting because; it receives highest solar irradiance as well as solar illuminance among all vertical surfaces. Daily average solar global illuminance on south surface for all the stations is shown in Figure 10. It is observed that for most of the stations, highest illuminance occurs during winter month of November and December. In winter, solar incident angle on the south surface is steeper, resulting in higher beam illuminance and hence higher global illuminance on the surface. Higher values of daily average illuminance for all the stations are found to be in the range of 45–55 klx. Peak values of daily average illuminance at each stations are as follows: New Delhi, 49–51 klx in the months of November and December; Jodhpur, 45–46 klx during December and January; Pune, 53 klx in November and January; Kolkata, 44–46 klx in November and January; Shillong, 50–52 klx in November and December; Leh, 40–46 klx in October and November. South surface receives lower daily average illuminance during the summer period due to the larger solar incidence angle that causes lesser beam illuminance, and hence lesser global illuminance on the south surface. Daily average global illuminance in summer season is as follows: 20–27 klx for New Delhi, 18–24 klx for Jodhpur and Pune stations, 20–26 klx for Kolkata station, 15–25 klx for Shillong station, whereas Leh station receives 15–20 klx. Global illuminance shows increasing trend during monsoon period for all the stations.

Figure 11 shows daily average diffuse illuminance on the south surface. It is almost uniform, and there is no drastic variation throughout the year for all the stations. Annual variations of diffuse illuminance for all the stations are: 16–20 klx for New Delhi and Kolkata, 11–18 klx for Jodhpur, 14–20 klx for Pune, Shillong, and Leh.

4.3.3. Daily average illuminance on the east surface
The daily average solar global illuminance on east surface for all the stations is shown in Figure 12. It is observed that for most of the stations, highest illuminance occurs during summer months of April and May. The peak daily average illuminance for all the stations is observed in the range of 20–35 klx (approx.). The peak daily average illuminance for each station is as follows: 31–36 klx for New Delhi, in the months of November and December; 26 klx for Jodhpur and Pune, in April and June; 22–32 klx (approx.) for Kolkata and Shillong, in April and June; 27 klx for Leh, in September and October. During monsoon, it is observed that all the stations except Shillong show decreasing trends of illuminance. Global illuminance during monsoon for each station is as follows: 30 klx for New Delhi; 22–23 klx for Jodhpur, Pune, and Shillong; 25–26 klx for Kolkata and Leh. Global illuminance in winter season (December to February) found to show lower levels except Shillong station, the range of values is: 27–30 klx for New Delhi station; 17–18 klx for Jodhpur and Pune stations; 23 klx for Kolkata. Shillong station receive high range of 27–32 klx, whereas Leh receives 14–15 klx.

Daily average solar diffuse illuminance (Figure 13) is found to attain maximum level at the end of summer season for the following three stations: New Delhi (22 klx), Jodhpur (19 klx) and Pune (20 klx), whereas it attains maximum during monsoon season for the following stations: Kolkata (22 klx), Shillong (19 klx), Leh (17 klx). During winter, Low range of diffuse illuminance (10–13 klx. approx.) is observed for all the stations.

4.3.4. Daily average illuminance on west surface
The daily average solar global illuminance on the west surface for all the stations is shown in Figure 14. For most of the stations, highest illuminance occurs during summer months of April and May. For each station, peak values are found to be in the range of 28–35 klx (approx.) and the details are as follows: 25–28 klx for New Delhi; 30–35 klx for Jodhpur and Pune; 27–28 klx (approx.) for
Kolkata and Shillong; 28 klx for Leh station. During the monsoon period, average illuminance received by this surface is as follows: 24 klx for New Delhi and Pune, 27 klx for Jodhpur, 19–22 klx for Shillong and Kolkata. Daily average global illuminance in winter season attains lower level for most of the stations, the range of values is: 19–23 klx for New Delhi; 23–26 klx for Jodhpur; 30–32 klx for Pune; 20–23 klx for Kolkata and Shillong, whereas Leh station receives 17–19 klx of illuminance. Results show that Jodhpur and Pune receive more global illuminance on the west surface as compared to those levels on the east surface. Whereas, New Delhi, Kolkata Shillong found to receive lower global illuminance on the west surface as compared to the corresponding levels on the east Surface.

Diffuse illuminance (Figure 15) on the west surface is found to attain maximum level at the end of summer season for the following three stations: New Delhi (22 klx), Jodhpur (19 klx) and Pune (20 klx). Whereas, it attains maximum during the monsoon season for the following three stations: Kolkata (22 klx), Shillong (19 klx) and Leh (17 klx). Diffuse illuminance falls to Lower levels (10–13 klx) during the winter season.

Overall quantitative assessment shows that most of the stations under study, receive solar global illuminance during summer months, as follows: 20–35 klx on east surface, 20–30 klx on west surface, 15–25 klx on south surface and 10–15 klx on north surface. During monsoon months, it is observed that south and east surfaces receive high range of global illuminance (20–30 klx) and west surface receives 20–25 klx of daily average global illuminance, whereas north surface receives low range of global illuminance (10–15 klx). During winter months, south surface receives highest daily average illuminance to the tune of 45–50 klx, east and west surfaces receive 20–30 klx, whereas north surfaces receive low range of 5–10 klx of daily average global illuminance.

4.4. Qualitative assessment of daylight on vertical surfaces

Magnitude of solar illuminance and duration of its availability are some of the most critical input parameters required for the design of a glazing in daylight conscious buildings. In this view, qualitative assessment of daylight on vertical surfaces for six Indian stations has been carried out through cumulative frequency of solar illuminance for a TMY. Qualitative assessment of daylight involves evaluation of the duration of occurrence (percentage of annual day time hours) for the availability of certain range of solar illuminance. The qualitative assessment of daylight for four vertical surfaces at six stations of India is presented in subsequent section.

4.4.1. Cumulative frequency of solar illuminance on the north surface

Cumulative frequencies of solar global illuminance and solar diffuse illuminance, on the north surface for all the stations, are shown in Figure 16(a) and (b) respectively. From Figure 16(a), it is observed that hourly global illuminance varies in the range of 0–40 klx, in a TMY for all the stations.
For 68–77% of day time in a year, most of the stations receive solar global illuminance in the range of 5–20 klx. For the solar illuminance of 5–10 klx, annual occurrence time at each station is: 40% for Jodhpur, Pune, Shillong and Leh; 30% for Kolkata, whereas it is 27% for New Delhi. For solar illuminance in the range 10–20 klx, the available time in TMY is: 50% for New Delhi, 40% for Kolkata, 35% for Pune and Shillong, 30% for Leh and 25% for Jodhpur.

4.4.2. Cumulative frequency of solar illuminance on the south surface
Figure 17(a) and (b) shows cumulative frequencies of solar global illuminance and solar diffuse illuminance respectively, on the south surface at all the stations. It is interesting to note that most of the stations, except cold zone stations, receive global illuminance in the range of 5–20 klx for 25% of annual day time, whereas cold zone stations (Leh and Shillong) receive it for 30% of annual day time. For the global illuminance of 20–40 klx, the duration of occurrence is in the range of 25–30% of annual day time for all the stations. The stations with more duration of occurrence, in increasing order are: Jodhpur, Leh, New Delhi, Shillong, Pune and Kolkata. Most of the stations except cold zone station, receive global illuminance in the range 40–60 klx for 18–20% of annual day time, whereas cold zone stations receive it for 15% of annual day time.

Related to solar diffuse illuminance on the south surface, it varies in the range of 0–50 klx for the whole year. For the solar diffuse illuminance of 10–30 klx, the occurrence time is in the range of 55–65% of annual daytime. Stations with more duration of occurrence, in increasing order, within the range of 55–65%, are: Leh, Shillong, Kolkata, Pune, New Delhi and Jodhpur.

4.4.3. Cumulative frequency of solar illuminance on the east surface
Cumulative frequencies of solar global illuminance and solar diffuse illuminance, on the east surface for all the stations, are shown in Figure 18(a) and (b), respectively. For the global illuminance in the range 5–20 klx, annual duration of occurrence at all the stations is: 35% for New Delhi and Kolkata, 50% for Jodhpur and Leh, 45% for Pune and it is 40% for Shillong. Similarly, for the illuminance in the range of 10–30 klx, duration of occurrence is: 35% for New Delhi and Kolkata, 33% for Jodhpur and Shillong and 40% for Leh and Pune. For solar global illuminance in the range 30–60 klx, the annual occurrence time is about 18–28%. Related to solar diffuse illuminance on east surface, it varies in the range of 0–40 klx for the whole year. It is observed that for the diffuse illuminance of 5–20 klx, occurrence time is in the range of 40–60% of annual day time. Stations receiving illuminance in this range, in increasing order are: Kolkata, New Delhi, Shillong, Pune, Jodhpur and Leh.

4.4.4. Cumulative frequency of solar illuminance on the west surface
Cumulative frequencies of solar global illuminance and solar diffuse illuminance, on the west surface for all the stations, are shown in Figure 19(a) and (b), respectively. For the global illuminance in
the range of 5–20 klx, duration of occurrence in terms of percentage of TMY is: 43% for New Delhi and Kolkata, 39% for Jodhpur and Pune, 45% for Pune and Shillong and 47% for Leh. For the global illuminance in the range of 10–30 klx, duration of occurrence for the each station is: around 48% for New Delhi and Kolkata; 26% for Jodhpur; 40% for Shillong and Leh; and 33% for Pune. Similarly, for the global illuminance of 30–60 klx, duration of occurrence is in the range of 20–30%. The stations with more duration of occurrence, in increasing order are: Leh, Shillong, Jodhpur, Kolkata, Pune and New Delhi.

Related to solar diffuse illuminance on the west surface, it is found to vary in the range of 0–40 klx for the whole year. Figure 19(b) shows that solar diffuse illuminance, in the range of 5–20 klx, occurs for 55–60% of annual daytime for all the stations. Stations with higher occurrence time are: Kolkata, New Delhi, Shillong, Jodhpur, Pune and Leh. Whereas, for the range of 20–40 klx of illuminance, annual duration of occurrence is: 25% for cold zone stations, 29% for Pune, 35% for New Delhi and Kolkata, whereas it is 17% for Jodhpur.

Overall qualitative assessment shows that for the solar global illuminance of 5–20 klx, annual duration of occurrence is as follows: 70–75% for north surface; 25–30% for south surface; 35–50% for east surface; and 40–45% for west surface. For solar global illuminance of 20–40 klx, details of the annual duration of occurrence are as follows: 3–8% for north surface, 25–30% for south surface, 20–25% for east surface and 20–30% for west surface.
5. Conclusions
Qualitative and quantitative assessment of outdoor daylight is extremely important for the design of daylight systems, so that the diverse benefits of daylight for indoor visual comfort could be reaped and appreciated. Empirical model for solar global illuminance on four cardinal vertical surfaces at New Delhi has been experimentally validated. Model derived global illuminance on vertical surfaces is very close to measured illuminance with MBE of −8.65% for the north surface, 0.30% for the south surface, 3.87% for the east surface and 7.89% for the west surface. The model is further used for computation of daylight for vertical surfaces at different climate specific stations of India. Hourly values of daylight data are analysed qualitatively and daily average values of daylight are assessed quantitatively for all the stations. Approximate peak global illuminance for all the stations is found to be: 14–15 klx for north surface, 45–50 klx for south surface, 25–35 klx for both the east and west surface, whereas lower range of global illuminance is found to be: 5–7 klx for north surface, 15–20 klx for south surface, 15–25 klx for east and west surface. Qualitative analysis of hourly solar illuminance for the north surface shows that most of the stations, receive 5–20 klx of solar global illuminance, for 70–75% of annual daytime.

For global illuminance of 30–60 klx for south surface, annual daytime for all the stations is 35% for New Delhi and Kolkata, 30% for Jodhpur and Pune and 28% for Shillong and Leh. Similarly for global illuminance of 10–30 klx on east surface, the availability is 40% for Pune and Leh, 37% for New Delhi and Kolkata and 34% for Jodhpur and Shillong.

There is an ample scope for research on daylight data generation for vertical surfaces at the stations for which solar irradiance data are available but daylight data are hardly available. Most of the stations of developing countries don’t have daylight data. There is a need to generate daylight contour map for a country so that daylight potential and its energy conservation potential, CO₂ mitigation, could be quantified. Further, the study can be extended to develop analytical models and software tools for the evaluation of indoor illuminance from various daylighting systems in order to assess the economical and environmental benefits of the daylight in buildings.

Nomenclature

| Symbol | Definition                          |
|--------|------------------------------------|
| \(\alpha\) | altitude of sky element (radian) |
| \(\alpha_s\) | solar altitude angle (radian)     |
| \(\gamma\) | azimuth of sky element (radian)   |
| \(\gamma_s\) | solar azimuth angle (radian)      |
| \(\gamma_{sur}\) | surface azimuth angle (radian)   |
| \(\rho\) | ground reflectivity (dimensionless) |
| \(\theta_t\) | solar incident angle on vertical surface (radian) |
| \(\theta_z\) | solar zenith angle (radian)       |
| \(I_{dh}\) | solar diffuse radiation on a horizontal surface (W/m²) |
| \(I_{bn}\) | solar beam radiation at normal incidence (W/m²) |
| \(I_{gh}\) | solar global radiation on a horizontal surface (W/m²) |
| \(I_o\) | extraterrestrial solar radiation at normal incidence (W/m²) |
| \(L_{bv}\) | beam illuminance on vertical surface (klx) |
| \(L_{dh}\) | diffuse illuminance on horizontal surface (klx) |
| \(L_{dm}\) | daily average illuminance (klx)    |
| \(L_{ph}\) | global illuminance on horizontal surface (klx) |
L_{gr} \quad \text{ground reflected illuminance on vertical surface (klx)}

L_{tv} \quad \text{total illuminance on vertical surface (klx)}

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