New features to the night sky radiance model illumina: Hyperspectral support, improved obstacles and cloud reflection

M. Aubé\textsuperscript{a,b,}\textsuperscript{*}, A. Simoneau\textsuperscript{a,b}

\textsuperscript{a}Cégep de Sherbrooke, 475, rue du Cégep, Sherbrooke, Québec J1E 4K1, Canada
\textsuperscript{b}Bishop’s University, 2600 rue College, Sherbrooke, Québec J1M 1Z7, Canada

A R T I C L E   I N F O

Article history:
Received 7 November 2017
Revised 27 February 2018
Accepted 28 February 2018
Available online 1 March 2018

Keywords:
Light pollution
LED Streetlight
Radiative transfer
Sky brightness
Hyperspectral
Cloud scheme
Sub-grid obstacles

A B S T R A C T

Illumina is one of the most physically detailed artificial night sky brightness model to date. It has been in continuous development since 2005 [1]. In 2016–17, many improvements were made to the Illumina code including an overhead cloud scheme, an improved blocking scheme for subgrid obstacles (trees and buildings), and most importantly, a full hyperspectral modeling approach. Code optimization resulted in significant reduction in execution time enabling users to run the model on standard personal computers for some applications.

After describing the new schemes introduced in the model, we give some examples of applications for a peri-urban and a rural site both located inside the International Dark Sky reserve of Mont-Mégantic (QC, Canada).

© 2018 Elsevier Ltd. All rights reserved.

1. Introduction

The main goal of this paper is to provide a description of new features incorporated in the sky brightness model named Illumina [1–3]. This radiative transfer model aim to simulate the measurements from a virtual spectrometer located anywhere in the world and looking toward any viewing angle. Illumina uses some ray tracing and statistical optimization techniques to reduce the computation time and a voxel-based simulation domain characterized by: 1) A radiant flux map of the light sources in the territory; 2) the angular photometry and spectral power distribution (SPD) of these light sources; and 3) a description of the spectral and geometrical properties of the environment (e.g. the spectral reflectance of the ground, the size and density of the obstacles, the orography). The model then calculates the path of a statistically selected set of photons exiting the light sources of the domain to every point in the line of sight. The first and second order of scattering is considered along with possible reflections on the ground surface. Illumina can be freely downloaded [4] and used by anyone since the code is released under GNU Public Licence.

The new features that will be presented here are: 1) The implementation of hyperspectral capabilities; 2) the improvement of the subgrid obstacle blocking scheme; and 3) the addition of a diffuse reflection cloud scheme.

In this paper, case studies, applied to the Mont-Mégantic Dark Sky Reserve (QC, Canada), will be presented to illustrate the new possibilities provided by the novelties of the model.

2. Implementation of the hyperspectral capabilities

By doing hyperspectral computations for a number of user-defined spectral bands, it is possible to generate the sky brightness maps and spectra for any combination of lamp technologies. For each pixel, one can define the net spectrum and the net angular photometry describing the lighting infrastructure. This makes it easy to quickly see what would happen to the night sky spectra or to any of its integrations (e.g. scotopic or photopic integration) if the lighting technology is changed over a given area. Such capabilities can be used as a knowledge transfer tool for cities managers, lighting professionals, managers of Dark Sky Reserves and world-class astronomical infrastructures. Moreover, Illumina can be a very effective tool in communicating the results to non technical population of the massive transition of outdoor night lighting to phosphor-converted Light Emitting Diode (LED) technology.

As an important input to the Illumina model, the spectral radiant flux map is created using data from: 1) The Visible Infrared Imaging Radiometer Day Night Band (VIIRS-DNB, [5]); 2) the ground reflectance product of the Moderate Resolution Imaging

\textsuperscript{*}Corresponding author.

\textit{E-mail address: martin.abe@cegepsherbrooke.qc.ca} (M. Aubé).

https://doi.org/10.1016/j.jqsrt.2018.02.033
0022-4073/© 2018 Elsevier Ltd. All rights reserved.
Spectroradiometer (MODIS, [6]); and 3) the approximate geographical inventory of the averaged angular light output pattern (LOP) and spectral power distribution (SPD) of light sources per zone. With the hyperspectral capabilities of Illumina, it is possible to correct for the very low spectral sensitivity of the VIIRS DNB sensor in the blue region. This is very important for not underestimating the emission of the blue rich “white” phosphor converted LEDs for the zones that have experienced recent conversion to white LEDs.

Let us define the light radiation pattern \( G(z, \phi, \lambda) \) which is expressed in units of \( \text{sr}^{-1} \text{nm}^{-1} \). \( z \) is the zenith angle, \( \phi \) is the azimuthal angle, and \( \lambda \) is the wavelength. The product of \( G(z, \phi, \lambda) \) with the radiant flux \( \Phi_e \) [W] defines the spectral intensity \( I_e \) [W/sr/nm] leaving the light source pixel at any angle.

\[
L_e(z, \phi, \lambda) = G(z, \phi, \lambda) \Phi_e
\]

For our modeling purposes, where many lamps of various azimuthal orientations fall into a single pixel, we can get rid of the azimuthal dependency. Thus we can average the angular photometry function horizontally to obtain the spectral light output pattern of a pixel \( \tilde{G}(z, \lambda) \) defined as

\[
\tilde{G}(z, \lambda) = \frac{1}{2\pi} \int_{0}^{2\pi} G(z, \phi, \lambda) \, d\phi
\]

(Eq. (1)) can be rewritten as follow

\[
L_e(z, \lambda) = \tilde{G}(z, \lambda) \Phi_e
\]

and \( \tilde{G}(z, \lambda) \) should be normalized over all possible solid angles and wavelengths.

\[
2\pi \int_{0}^{\pi} \int_{z=0}^{z=\pi} \tilde{G}(z, \lambda) \sin(z) \, dz \, d\lambda = 1
\]

The signal sensed by the VIIRS–DNB sensor in units of Wsr\(^{-1}\)cm\(^{-2}\) is given by:

\[
\text{DNB} = \frac{\Phi_e}{S} \int_{\lambda} R(\lambda) T(\lambda) \left( \frac{\pi}{1} \rho(\lambda) F_{500-1800}(\lambda) + (\tilde{G})_{0-56}(\lambda) \right) d\lambda
\]

Where \( R(\lambda) \) is the spectral sensitivity of the VIIRS sensor. \( T(\lambda) \) is the atmospheric transmittance between the ground pixel and the VIIRS sensor. \( \Phi_e \) is the radiant flux of the lamps contained in the pixel. \( S \) is the area of the pixel in cm\(^2\) (which is \( 10^{10} \) for a pixel of \( 1 \times 1 \) km). \( F_{500-1800}(\lambda) \) and \( (\tilde{G})_{0-56}(\lambda) \) are respectively the amount of light going down per unit of wavelength, and the average value of \( G(z, \lambda) \) over the possible viewing angles of the VIIRS–DNB (from 0 to 56\(^\circ\)). The VIIRS–DNB images are monthly composites which imply an average of many data taken at different angles between 0\(^\circ\) to 56\(^\circ\) during the month.

\[
F_{500-1800}(\lambda) = \int_{z=0}^{\pi} 2\pi \sin(z) \tilde{G}(z, \lambda) \, dz
\]

\[
(\tilde{G})_{0-56}(\lambda) = \int_{z=0}^{56} \sin(z) \tilde{G}(z, \lambda) \, dz
\]

The light radiation pattern \( \tilde{G}(z, \lambda) \) for a given pixel is assumed to always be obtainable by executing a linear combination of the SPDs and LOPs of the various lamps encountered in a pixel, even if that might not always be true.

\[
\tilde{G}(z, \lambda) = \frac{\sum_{i} A_i \tilde{f}_i(\lambda) LOP_i(z)}{2\pi \int_{0}^{\pi} \sum_{i} A_i \tilde{f}_i(\lambda) LOP_i(z) \sin(z) \, dz \, d\lambda}
\]

By definition, \( \sum_i A_i = 1 \). \( \tilde{f}_i(\lambda) \) is the SPD of lamp \( i \) in the pixel normalized to one lumen [W/sr/nm/Lm]. Eq. (10) is used to normalize the SPD.

\[
\tilde{f}_i(\lambda) = \frac{f_i(\lambda)}{\int_{\lambda}^{\lambda} f_i(\lambda) V(\lambda) j(\lambda) \, d\lambda}
\]

(10)

\( f_i(\lambda) \) is the unnormalized SPD of lamp \( i \) and \( V(\lambda) \), the CIE standard photopic response.

The radiant flux of the pixel \( \Phi_e \) is obtained using the formula:

\[
\Phi_e = \int_{\lambda} R(\lambda) T(\lambda) \left( \frac{\pi}{1} \rho(\lambda) F_{500-1800}(\lambda) + (\tilde{G})_{0-56}(\lambda) \right) d\lambda
\]

(11)

In this paper, we decided to neglect the spectral transformation exerted by the atmospheric transmittance \( T(\lambda) \). A complete description should include this effect caused by absorption and scattering along the atmospheric path between the light sources and the satellite to obtain a proper absolute estimation of \( \Phi_e \). However, in the present study, not taking this effect into account underestimates the amount of blue, which is not seen by the VIIRS–DNB sensor, mitigating the error made. Atmospheric correction will be added in the next version of the model.

2.1. Preprocessing steps to generate the ground based light inventory

The simulation domain is divided in multiple overlapping circular zones in which the light inventory is assumed to be constant. For each of these geographical zone, multiple preprocessing steps must be done to produce the inputs necessary to execute the model. Here is the summary of the steps to accomplish.

1. Normalize the lamps spectra using Eq. (10).
2. Normalize the lamps LOPs using Eq. (9).
3. Calculate \( G(z, \lambda) \) with Eq. (8) where \( A_i \) must be determined by a local expert.
4. Calculate \( F_{500-1800}(\lambda) \) with Eq. (6).
5. Calculate \( (\tilde{G})_{0-56} \) with Eq. (7).
6. Calculate \( \Phi_e \) with Eq. (11).
7. For each pixel and each spectral band defined by the interval \([\lambda_n, \lambda_{n+1}]\) compute the average LOP for the band.

\[
\langle LOP \rangle_n(z) = \frac{\int_{\lambda_n}^{\lambda_{n+1}} \tilde{G}(z, \lambda) \, d\lambda}{\int_{\lambda_n}^{\lambda_{n+1}} \int_{0}^{\pi} \tilde{G}(z, \lambda) \sin(z) \, dz \, d\lambda}
\]

(12)

8. For each pixel and each spectral band compute the spectral flux of the given band in W/nm.

\[
\langle f \rangle_n = \frac{2\pi \Phi_e}{\lambda_{n+1} - \lambda_n} \int_{\lambda_n}^{\lambda_{n+1}} \int_{0}^{\pi} \tilde{G}(z, \lambda) \sin(z) \, dz \, d\lambda
\]

(13)

At the end of that process, we have in hand one file containing the LOP and another containing the flux for each spectral band and each geographical zone.

3. Correction for subgrid obstacles

The subgrid obstacles are defined by three numbers for each pixel of the simulation domain, as seen in Fig. 1. These include both the averaged distance between the light source and the obstacles, and the averaged obstacle height. When combined with the averaged height of the light sources, also defined independently for each pixel of the domain, it allows for the determination of which light rays leaving the source, scattered by the atmosphere, or reflected by the ground will be blocked by subgrid obstacles. However, since trees and building don’t usually provide a perfect obstruction of the light, as rays can pass through leaves and between the buildings or are simply not blocked along the street direction.
Table 1
Estimates of reflectance for overcast cloud layers according to Shapiro [7]; $\theta$ is the incident zenith angle of the light to the clouds. The clouds are defined as follows: Cirrus (Ci), Cirrostratus (Cs), Altostratus (As), Altocumulus (Ac), Cumulus (Cu), Cumulonimbus (Cb), Stratus (St), Stratocumulus (Sc).

<table>
<thead>
<tr>
<th>Cloud type</th>
<th>$\cos(\theta)$</th>
<th>0.05</th>
<th>0.15</th>
<th>0.25</th>
<th>0.35</th>
<th>0.45</th>
<th>0.55</th>
<th>0.65</th>
<th>0.75</th>
<th>0.85</th>
<th>0.95</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin Ci/Cs</td>
<td>0.240</td>
<td>0.235</td>
<td>0.211</td>
<td>0.170</td>
<td>0.143</td>
<td>0.134</td>
<td>0.120</td>
<td>0.106</td>
<td>0.103</td>
<td>0.100</td>
<td></td>
</tr>
<tr>
<td>Thick Ci/Cs</td>
<td>0.568</td>
<td>0.535</td>
<td>0.460</td>
<td>0.401</td>
<td>0.342</td>
<td>0.297</td>
<td>0.273</td>
<td>0.249</td>
<td>0.240</td>
<td>0.240</td>
<td></td>
</tr>
<tr>
<td>As/Ac</td>
<td>0.650</td>
<td>0.645</td>
<td>0.621</td>
<td>0.604</td>
<td>0.587</td>
<td>0.576</td>
<td>0.569</td>
<td>0.562</td>
<td>0.560</td>
<td>0.560</td>
<td></td>
</tr>
<tr>
<td>Cu/Cb</td>
<td>0.661</td>
<td>0.650</td>
<td>0.636</td>
<td>0.611</td>
<td>0.592</td>
<td>0.575</td>
<td>0.561</td>
<td>0.549</td>
<td>0.535</td>
<td>0.530</td>
<td></td>
</tr>
<tr>
<td>Sc/St</td>
<td>0.703</td>
<td>0.693</td>
<td>0.676</td>
<td>0.660</td>
<td>0.648</td>
<td>0.639</td>
<td>0.629</td>
<td>0.620</td>
<td>0.613</td>
<td>0.609</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1. Light source and obstacles geometry. $h_{L}$ is the light source height relative to the ground, $h_{O}$ the obstacles height relative to the ground and $d_{O}$ the “average” distance between the light source and the obstacles that is assumed to be the half of the average distance between obstacles.

we also defined the opacity (or obstacle filling factor $F$) of the subgrid obstacles. The light rays interacting with the subgrid obstacles will be able to randomly pass trough and propagate into the environment with a probability $p = 1 - F$.

In order to correct the flux contribution to the sky radiance for a given light path, its value is multiplied by the probability $p$ above mentioned. Meaning that a filling factor of $F = 1$, that correspond to a pass trough probability of $p = 0$, will completely attenuate the contribution. At the other end, a filling factor of $F = 0$ will give a probability of 1, implying that all the light will contribute to the sky brightness.

4. Scattering by overhead clouds

To incorporate clouds in the already existing model, we need to determine the clouds base height and assume that no light can penetrate through, making it the effective maximum height of the atmosphere. We also need to define an hemispherical reflectance function for the cloud base surface which will depend on the cloud type. The hemispherical reflectance of different types of clouds has already been studied long ago by Shapiro [7].

The parametrization proposed by Shapiro [7] is quite simple as it relies on the definition of a cloud base height per cloud type and a table giving the hemispherical reflectance $R(\theta)$ of each cloud type at 10 different incident angles $\theta$. The amount of light reflected is determined by the indicence angle. In Table 1, $\cos(\theta)$ increases by bounds of 0.10. The software Ftyk was used to estimate a Gaussian curve (Eq. (14)) that would allow us to have a continuous function to be used for any incident angle $\theta$ in the model. The cloud base surface is assumed to be well approximated by a Lambertian reflectance law.

The form of the function for the reflectivity of the cloud would therefore be:

$$R(\theta) = A + a_{0} \exp \left( - \frac{\cos(\theta)}{a_{1}} \right)^{2}$$

(14)

Where $A$, $a_{0}$, and $a_{1}$ are constants that define the reflectivity of a given cloud type. After fitting the data of Table 1, we obtained the parameters of Eq. (14) for each cloud type. The results are shown in Table 3.

5. Applications for peri-urban and rural sites

In this section we will show some effects of the newly added features to the model for two different geographical cases, both located in the province of Quebec in Canada. The first one, Sancy, is a site located about 3 km from the edge of the city of Sherbrooke, Quebec, Canada. The second one, Mont-Mégantic Observatory (MMO), is located on top of Mount Mégantic about 60 km away from Sherbrooke. Both sites lie inside the first international dark sky reserve of Mont-Mégantic. This reserve has been recognized by the International Darksky Association in 2007.

Sherbrooke is a city of about 200 thousands inhabitants. Since 2013, any change to its lighting infrastructure have been guided by a new regulation where, in most applications, the new lighting installation must contain less than 10 percent of blue light, corresponding to the blue content of a typical High Pressure Sodium (HPS) lamp. In this case the blue light is defined as the ratio of the flux between 405–530 nm reported on the total flux between 380–730 nm. Thanks to this new regulation, most new streetlight installations or replacements have been done using PC amber LEDs. PC amber LEDs have much lower blue content than HPS while providing a better color rendering than HPS. Along with a prescribed reduction of the ground level illuminance, and the better concentration of the light on the desired surface, the regulation is very effective in reducing the light pollution produced by the city. Nevertheless, Sherbrooke still creates the most important light dome in the sky of MMO. Fortunately this dome is restricted to the near horizon angles and contribute only to 3.3% of the zenith sky radiance associated to sodium spectral line at 589 nm [8]. For a more detailed description of the Mont-Mégantic dark sky reserve, please refer to Aubé and Rody [8]. Fig. 2 illustrates the location of the experiment. In the right pane, we have put the VIIRS–DNB data as underlay. Note that for a better clarity, the contrast of the VIIRS–DNB have been increased on that image.

Prior to the modeling, some physical parameters have to be defined as inputs for the calculations. We decided to use uniform values for the aerosol optical depth at 500 nm of 0.09 and its associated Angstrom coefficient of 1.66. Such values were obtained from the Aerosol robotic network (AERONET) climatology [9]. We
assumed an aerosol composition to fit the rural model of Shettle and Fenn [10]. We also assumed a ground surface pressure of 101.3 KPa, and the relative humidity of the air was fixed to 50%. All light fixtures inside a circular zone of 30 km radius centered on the MMO were set to be 100% HPS with 1% of Upward light output ratio (ULOR). Sherbrooke city have been modeled assuming 100% HPS but with one third of 5% ULOR and two third of 1% ULOR. All other regions of the domain have been set to HPS with 5% ULOR. This lamp inventory will be referred to later on as the “HPS mix”. Typical obstacle height was set to 10 m and average distance between obstacles to 25 m. Lamp posts height were set to 7 m. For the reference case, the obstacles filling factor was set to 1, which is representative of the city center of Sherbrooke city and of its suburbs as long as there are still leaves in trees. We used the VIIRS–DNB composite of October 2016 and the MODIS reflectance composite of September 29, to October 6, 2016 for bands 1, 3, and 4, respectively 645 nm, 469 nm, and 555 nm (see Fig. 3(b)). Adding MODIS band 2 (858 nm) would improve the spectral reflectance information in the spectral range 700 to 800 nm but the lamps used in this experiment do not emit much at these wavelength. However, this band will be included by default in a future version of Illumina.

The spectrum was separated into 20 equal bandwidth from 400 to 800 nm (20 nm wide). The lamp spectra used for the modeling were extracted from the Light Spectral Power Distribution Database (LSPDD) [11] maintained by Dr Johanne Roby from Cégep de Sherbrooke. We specifically used lamps 2536 for HPS and 2501 for LED 3000 K. This LED lamp is used to infer what would happen if all the HPS lamps are replaced by LED 3000 K with 0% ULOR and also with 3000K LED with 5% ULOR. The lamp spectra used are shown in Fig. 3(a).

To highlight the effect of the hyperspectral support, sky spectral radiance of the two sites were calculated alternatively with HPS mix and LED 3000 K. We have generated allsky plots of the artificial scotopic brightness SB(z, φ) of the sky (ie. the sky radiance weighted by the scotopic response), along with the sky spectra toward zenith. The following equation was used to produce the allsky plots of SB(z, φ) from the modeled sky radiance L(λ, z, φ).

\[ SB(z, \phi) = \int_\lambda L(\lambda, z, \phi) \tilde{V}'(\lambda) d\lambda \]  

where the scotopic response \( \tilde{V}' \) was normalized according to the following equation.

\[ \tilde{V}' = \frac{V'}{\int_\lambda V'(\lambda) d\lambda} \]  

The effect of the obstacle filling factor was verified by modeling factors of F = 0.0, F = 0.5, and F = 1.0 (i.e. no obstacles, obstacles blocking half of the light and completely opaque obstacles).

For the clouds, we chose the Altostratus/Altocumulus cloud model with a cloud base height of 4 km (Table 2).

5.1. Peri-urban site: Sanctuaire de Beauvoir

This site is located northward from Sherbrooke at ∼3 km from the city edge and about 6 km from the city center. The coordinates of the site are 45.455 degrees N, 71.898 degrees W. The site
LED with 5% ULOR (Fig. 5(c)) shows that such a change should be accompanied with an increase of the scotopic luminance by a factor of ~4. But as said, the HPS mix case has a lower ULOR than the LED 5% ULOR case which may explain an important part of this increase. One very interesting result is the fact that, while the use of 0% ULOR (Fig. 5(b)) reduces the scotopic sky luminance by a factor of ~6 compared to 5% ULOR, the scotopic sky luminance is extending much higher toward zenith with 0% ULOR lamps. This is saying that using lamps without uplight decreases the contrast between the near-horizon scotopic sky luminance and scotopic sky luminance at lower zenith angles. In Fig. 5(d) we can see the effect of an overcast sky with altostratus/alto-cumulus and cloud base height of 4 km. It is very interesting to notice the clumpy structure of the sky luminance in that case. Clumps are concentrated southward between 30 and 60 degrees of zenith angles. This range of angles correspond with the clouds sections right above the different parts of the city of Sherbrooke. The clumps are then clearly related to the upward emission of light from each ground based clumps of the city. To create such level of clumpiness, the upward light needs to be emitted as relatively concentrated beams similar to floodlights. Actually, this is the case because this modeling experiment considers the blocking by subgrid obstacles and in such situation, most of the direct and reflected light can escape the city in a restricted upward cone. This is because the subgrid obstacles structure can be assimilated to vertical tunnels with sides being made of vertical surfaces of the nearby obstacles (buildings walls and trees). Note that the clumpiness of the cloudy sky has been qualitatively observed by us on the site. Of course with real clouds, the light clumps may be even more clumpy because of the non-uniformity of real clouds. Our cloud scheme actually assume uniform cloud surface with no precipitation.

One other interesting feature of Fig. 5(d) is the light dome toward N-NW. This is likely to be the clouds lighted by remote cities of Asbestos/Danville and Victoriaville respectively located 35 and 65 km away from Sanctuaire de Beauvoir. This light dome is hardly seen during clear nights. Both Figs. 4(b) and 5(d) show the tremendous amplification of the scotopic sky luminance when the sky is cloudy. Here the scotopic luminance is ~10 times higher at zenith with clouds compared to without clouds. That level of amplification factor is coherent with previous measurement and modeling experiments [12–14].

Fig. 6 show the effect of the obstacles filling factor on the modeled sky luminance. Comparison between Fig. 6(a) and Fig. 6(c) show that having opaque obstacles can reduce the scotopic sky luminance by a factor of ~5 compared to no obstacles. Having $F = 0.5$ result in a scotopic sky luminance a bit lower to the average of $F = 0$ and $F = 1$, which indicate that the subgrid blocking is not linear.
Fig. 5. Scotopic sky luminance at peri-urban site of Sanctuaire de Beauvoir.

(a) HPS mix

(b) LED 0% ULOR

(c) LED 5% ULOR

(d) HPS mix with clouds

Fig. 6. Scotopic sky luminance at peri-urban site of Sanctuaire de Beauvoir assuming the HPS mix with and without clouds for different obstacle filling factors.

(a) $F = 1$

(b) $F = 0.5$

(c) $F = 0$

(d) $F = 0.5$ with clouds
5.2. Rural site: Observatoire du Mont-Mégantic

This site is located eastward from Sherbrooke at ~60 km from the city center. The coordinates of the site are 45.460 degrees N, −71.154 degrees W at 1111 m above see level.

Fig. 7 shows how the zenith sky spectrum vary as a function of the lighting technology. As for the peri-urban site, one can notice that the sky radiance is a lot higher with 3000K LED 5% ULOR. The LED 0% ULOR is more representative of typical LED transition but one must consider an additional reduction ranging between 30% and 50% because of the usual luminous flux reduction when HPS are being replaced by LEDs. One important difference between the rural site and the peri-urban site is that the 0% ULOR case is a lot more attenuated than the 5% ULOR in the rural context. This is because of the longer light path involved and then the spectrum is much more attenuated by the Rayleigh scattering while the bluing effect of the ground reflectance being the same as for the peri-urban case. One other very interesting features is the lower cloud amplification effect of the zenith radiance for the rural case in comparison to the peri-urban case. Actually at MMO, the cloud amplification factor at zenith is ~4 while it was ~20 for the peri-urban case. This reduction of the cloud amplification factor can be explained by the fact that the main sources of light pollution are more distant in the rural case (dozens of km compared to few km for the peri-urban case). This larger distance combined to the beam like emission pattern toward clouds greatly reduce the amount of direct light reaching the clouds because of the larger zenith angles involved.

Fig. 8 shows the scotopic sky luminance for the rural site of the Mont-Mégantic observatory. The comparison between 8(a) and 8(c)
show that such a change should be accompanied with an increase of scotopic luminance by a factor of $\sim 3$ which is a bit less than what would happen for the peri-urban site. The use of 0% ULOR (8(b)) reduce the scotopic sky luminance by a factor of $\sim 3.5$ compared to 5% ULOR this is much lower than the peri-urban case. In other words, the reduction of the ULOR would have a more important impact in sites closer to light pollution sources. Like for the peri-urban site, the scotopic sky luminance is extending higher toward zenith with 0% ULOR lamps but is less obvious for the rural site than for the peri-urban site. In Fig. 8(d) we can see the effect of an overcast sky. Again we used altostratus/altocumulus clouds with cloud base height of 4 km. Here the clumpy aspect of the sky is not observed and this is probably because no important source of light are closer than 10 km and the high elevation of the site. Both effects should push any clumps close to the horizon and render them hardly distinguishable from usual near horizon light domes. Note that the presence of clouds change the angular distribution of the light domes in the sky. Without clouds, the most important dome is toward Sherbrooke while with clouds it is toward Lac Mégantic, a much smaller city located closer at $\sim 25$ km NE. Comparing Fig. 8(d) and (a) highlight the clouds amplification for the scotopic luminance. This amplification factor can reach a value of $\sim 24$ toward the city of Sherbrooke and this amplification effect is clearly not uniform over the sky.
Fig. 9 shows the allsky scotopic luminance with $F = 0$, $F = 0.5$ and $F = 1$. Comparison between Fig. 9(a) and (c) shows that having opaque obstacles can reduce the scotopic sky luminance by a factor of $\sim 4$ compared to no obstacles. This is a little bit lower that what would happen in the peri-urban site but it is still important.

5.3. The blue content of the night sky

In order to investigate how the color of the sky relates to the color of the lighting infrastructure, we calculated the blue content of the night sky and compared it to the blue content of the lighting infrastructure. In this process, the blue content was defined as the amount of radiance in the spectral range 400 to 500 nm reported to the total amount of radiance. Then we have produced all sky plots of the ratio of the blue content of the sky over the blue content of the lighting infrastructure. These all sky blue ratio maps are presented in Figs. 10 and 11 for both the peri-urban and rural sites under clear sky. One quick observation is that at the peri-urban site, darker skies tend to have higher blue content as seen by comparing, as an example, Fig. 10(a) and (b) with Fig. 6(a) and (b) respectively. This is because that darker parts of the sky contain relatively less direct light than brighter parts, meaning that the scattering is relatively more important in darker parts of the sky. Since Rayleigh scattering is more pronounced in the blue, we generally see an increased blue content for the optical paths dominated by scattered light. For the rural site however, we observe that it’s the direction toward light domes (compared to zenith) that tends to be more pronounced in the blue. Because of the long optical paths involved, the attenuation removes a larger amount of blue for the sky sectors opposed to the city direction. Overall, we also see more blue in the peri-urban site than in the rural site, which is also explained by the fact that blue light is more attenuated for longer optical paths.

6. Conclusion

This paper aimed to introduce to the scientific community three important new features of the sky brightness model Illumina. These features are opening new ranges of applications. We presented the results of a modeling experiment involving the variation of the related parameters for two very different contexts (rural and peri-urban) to show the novel possibilities associated with the new features added to Illumina.

Among the most important results we found were that the effects of Rayleigh scattering on the spectral composition of the artificial sky brightness is non-trivial and as such, the new hyper-spectral capabilities of the model allow a more in depth study of this phenomenon while also taking into account the spectral effect of ground reflectance. As shown, the spectral effect of the reflectance is linked to the level of sub-grid obstacle blocking. In other words, while obstacles do not provide direct spectral transformations to the light propagated, they produce an indirect spectral effect explained by a different combination of the scattered and reflected light, both highly spectrally dependent. We showed that both ground reflectance and atmospheric extinction attenuate the sky radiance in the blue part of the spectrum. The extinction being more important for the remote rural site, where the sky is less blue in that case.

We found that while the use of full cutoff lamps (0% ULOR) reduces the sky brightness, it decreases the contrast between the near-horizon sky brightness and sky brightness at lower zenith angles.

We also noticed the importance of the subgrid obstacles when determining the amount of light escaping from a city. Indeed, the presence of obstacles can reduce by a factor of 5 the sky brightness in both peri-urban and rural locations.

Lastly, clouds have a complex and notable effect on the sky radiance that, in the studied cases, increased the overall brightness by a factor up to 24. Clouds also reveal complex angular features of the sky brightness for the peri-urban site. The features appear to be linked to the nearby non uniformity of light sources along with obstacle shadowing.

Acknowledgments

We applied the sequence-determines-credit approach for the sequence of authors. This work was supported by the Fond Québécois pour la Recherche sur la Nature et les Technologies (FQRNT). Computation time on Mammouth serial II was provided by Compute Canada and Calcul Québec.

Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jqsrt.2018.02.033.

References


Aubé M, Roby J. Sky brightness levels before and after the creation of the first international dark sky reserve, Mont-Mégantic observatory, Québec, Canada. J Quant Spectrosc Radiat Transf 2014;139:52–63.


