Sky brightness levels before and after the creation of the first International Dark Sky Reserve, Mont-Mégantic Observatory, Québec, Canada

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ABSTRACT

In 2007, the area around the Mont-Mégantic Observatory (MMO) was officially certified by the International Dark-Sky Association and the Royal Astronomy Association of Canada as the first International Dark Sky Reserve (IDSR). In order to be able to investigate the impact of Artificial Light at Night on night sky brightness before and after the establishment of the IDSР, we used a heterogeneous artificial sky brightness model including an implicit calculation of 2nd order scattering (ILLUMINA) developed by Martin Aubé's group. This model generates three kinds of outputs: the sky radiance at the given site, observing angle and wavelength and the corresponding contribution and sensitivity maps. The maps allow for the identification of the origin of the sky radiance according to each part of the surrounding territory. For summer clear sky conditions, the results show that replacing light fixtures within a 25 km radius around the MMO with cut-off High Pressure Sodium devices and reducing the total installed radiant power to 40% of its initial level are very efficient ways of reducing artificial sky brightness. The artificial sky brightness reduction at zenith observed after the establishment of the IDSР was 50% in the 546 nm mercury spectral line, while the reduction obtained in the 569 nm sodium line was 30%. A large part of that reduction can be associated to the reduction in radiant power. The contribution and sensitivity maps highlight critical zones where any changes in the lighting infrastructure have the most important impact on sky brightness at the MMO. Contribution and sensitivity maps have been used to analyze the detailed origin of sky brightness reduction. The results of this study are intended to support authorities in the management of their lighting infrastructure with the goal of reducing sky brightness. The results have been shared with MMO officials and are being used as a tool to improve sky quality at the observatory.

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1. Introduction

Dark sky areas are now increasingly rare in the world and this is due to the constant growth of artificial light at night (ALAN). This phenomenon is largely the result of human activities and its primary sources are street lamps, advertising panels and lighted buildings. Astronomers were the first to point out that dark skies are disappearing when they realized that sky observation was becoming more difficult because of the bright halos caused by ALAN. It is only in the past decade that the multiple negative impacts of ALAN on fauna, flora and human health have been documented more intensively in the literature [1–3]. Artificial light produced by street lights has been identified as one of the major sources of night sky brightness.

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As such, sky brightness can be reduced by improving their performance. For example, a transition from the Cobrahead model street light, which emits \( \sim 6\% \) of its flux upward, to the Helios model, a cut-off street light which emits \( \sim 1\% \) of its flux upward, clearly reduces the total amount of light. In fact, the downward flux is largely absorbed by the ground, especially during the summer when there is no snow cover.

In 1978, a professional astronomical observatory located about 1100 m above sea level on top of Mont-Mégantic in the Eastern Townships, Québec (Canada) was inaugurated. The Mont-Mégantic Observatory (MMO) is equipped with a Ritchey–Chrétien telescope whose primary mirror is 1.6 m in diameter, making it the fourth largest in Canada and the largest in eastern North America. It is the best equipped astronomical observatory in Canada [5,6] and is located over 60 km from the closest urban center (Fig. 1). Its mission is to conduct astrophysical research and train young researchers for work in other major observatories around the world, thus exporting expertise from the Observatory. Also, the Observatory develops state-of-the-art instruments that are globally recognized for their high quality.

It is estimated that in 1979, the sky brightness at the summit of the MMO was around 25% higher than the natural sky brightness value. This evaluation was, unfortunately, only made qualitatively by observatory staff members. Despite being located far from major centers, sky brightness at the summit further increased, almost doubling, between 1979 and 1998 (i.e. an increase of \( \sim 4\% \) per year). This increase in sky brightness became a real threat to scientific studies and to the basic objectives of the MMO. Furthermore, the research, education and tourism activities in the region of Mont-Mégantic are based primarily on the astronomical observatory; the protection of the night sky is thus crucial for the local population.

Faced with these challenges, it became imperative to stop the growth of artificial lighting in order to reduce sky brightness. ASTROlab, a public outreach center, developed and implemented a light pollution abatement project that included the establishment of an International Dark Sky Reserve (IDSR) covering 5500 square kilometers around the MMO. This regional-scale initiative provided us with the unique opportunity to study the changes in artificial sky brightness parameters before and after the implementation of these protective measures.

In this paper, we will describe how light fixture parameters, properties of urban and rural environments (reflectance, obstacles and topography), wavelength, and atmospheric content may influence the level of sky brightness as a function of the viewing angle. Comparison of artificial sky brightness levels before and after the creation of the IDSR will also be shown. To achieve the level of sensitivity needed for the present study, we used a heterogeneous numerical radiative transfer model [8,9]. The results allow us to represent as faithfully as possible the phenomenon of artificial sky brightness as can be seen from a standing point at any horizontal and vertical viewing angle. In our study, the observer location was set to the MMO.

The model also produces contribution and sensitivity maps, two powerful tools that allow the identification of the origin of the artificial sky brightness and the most efficient ways to act in order to reduce it. By comparing the results for 2005 (before the creation of the IDSR) with the results for 2009 (after the creation of the IDSR) we will be able to monitor the impact of creating the IDSR on artificial sky brightness.

2. Methods

2.1. Background

2.1.1. The light pollution abatement project

In 2003, after considering several initiatives aiming to address the worsening sky brightness problem, a local public outreach center, ASTROlab, developed an ambitious light pollution abatement project to reduce artificial sky brightness.
brightness at the MMO by 50% to revert back to the brightness levels of 1979 [7].

The project focused on two zones concentrated inside a 50 km radius around the MMO (Zone 1: 0–25 km from the MMO, Zone 2: 25–50 km from the MMO) and a third zone corresponding to the city of Sherbrooke, which is located approximately 60 km from the MMO (Fig. 2). These intervention areas were determined according to their respective estimated sky brightness contribution at the MMO. The MMO is surrounded by several municipalities and, despite their small size, those located within a radius of 25 km contribute significantly to sky brightness. Fig. 3 shows a 360° panorama of the light domes as seen from the MMO in 2007 during the lighting devices conversion.

As of 2005, following important public awareness efforts, the municipalities involved with the project adopted regulations pertaining to the installation of new lighting devices. With the cooperation of businesses, industries and residents, a lighting device conversion program was initiated in order to convert existing light fixtures in the nearby municipalities to devices that were less powerful (approximately 40% lower radiant power), but more efficient; these fixtures significantly reduced light pollution without significant impact on the ambient light. In the conversion process, white lights like metal halide (MH) or mercury vapor (MV) lamps were replaced by high pressure sodium (HPS) lights (model: Helios). In 2007, over 3300 fixtures were replaced resulting in energy savings of nearly 2 GWh/year. The 40% radiant power average reduction has been obtained from statistical data provided by the MMO’s IDSR in their report to Hydro-Québec [4]. The impact on the starry sky was immediate and impressive.

2.1.2. Establishment of the Mont-Mégantic area International Dark Sky Reserve

In order to continue to pursue the project’s goals and help ensure their persistence in time, ASTROLab proposed the creation of the first International Dark Sky Reserve (IDSR) covering an area of nearly 5500 km² that includes two Regional County Municipalities, the city of Sherbrooke, 35 municipalities and over 225,000 citizens. Under the leadership of ASTROLab and with the help and strong support of numerous regional partners, such as the MMO and the Mont-Mégantic National Park, the Mont-Mégantic area IDSR was formally established in 2007 and is recognized by the International Dark-Sky Association and the Royal Astronomy Association of Canada (RASC). This official recognition favors the sustainability of the project by giving the local population a sense of pride about this accomplishment.
2.2. Modeling experiment

2.2.1. Light pollution numerical model: ILLUMINA

The radiative transfer model used for this study is ILLUMINA [8,9] version 2. This model is distributed under Gnu Public License and can be downloaded from Google Code [10]. In version 2, a statistical optimization procedure has been added for the selection of ground pixels and line of sight voxels to reduce computing time.

Basically, ILLUMINA acts as a ray tracing software where a set of photons are thrown from light fixtures above the ground cells and then reach the observer’s field of view after four different light paths: (1) single scattering by molecules and aerosol inside voxels of the line of sight \(I_1\); (2) single scattering after a lambertian reflection on the ground \(I_{g1}\); (3) 2nd order of scattering in the line of sight after a single scattering from an atmospheric voxel in a volume surrounding path between the source and the line of sight voxel \(I_{l2}\); and (4) same as path (3), but after a reflection on the ground \(I_{g2}\). The geometry of these light paths is illustrated in Fig. 4. Along with scattering processes toward the observer, extinction from aerosols (scattering and absorption) and molecules (scattering only) is computed for all light paths considered.

In 2007, Aubé [11] showed that the 2nd order of scattering may have a significant impact on artificial sky brightness, especially when the observer is far from cities. This phenomenon may be explained by the fact that the single scattering dome of light acts as a large source for the 2nd order of scattering process and thus its distance decreasing function is less steep when compared to point-like sources.

When 2nd order scattering is computed, the numerical approach is CPU time-consuming and requires access to a high performance computing infrastructure. In the model, the atmosphere is subdivided into 50 prescribed vertical levels, from the lowest altitude of the modeling domain to 30 km above. Thereby, the model accounts for about 99% of the atmosphere. Vertical level thickness is increasing with altitude in order to be more accurate at low altitude voxels where atmospheric concentration and light flux are most often higher. We assume exponential vertical profiles for aerosol and molecular concentrations. A scale height of 2 km was used for aerosols while 8 km has been adopted for molecules.

ILLUMINA computes optical impact of size distribution and composition of aerosol content using Mie theory for spherical particles; more complex particle shapes are not yet implemented, leading to a possible overestimate of the backscattering efficiency [12]. We are using the complex refractive index and bi-modal lognormal size distributions suggested by Shettle and Fenn [13]. The aerosol composition can be adjusted in accordance to modeling experiment particularities in terms of geography (rural, urban or maritime) or to account for special atmospheric events like important biomass burning, volcanic eruption or dust storms. ILLUMINA is a regional model, and thus the maximal domain size should not exceed a few hundred kilometers. We assume a plane-parallel atmosphere. The horizontal resolution typically ranges between 150 m and 1 km. Light Output Patterns (LOPs) for each horizontal cell are determined from a linear combination of illuminating Engineering Society of North America (IESNA) files corresponding to the different lamps found in this cell. We assume that LOP is isotropic along azimuth angles. This is realistic as long as many light fixtures with various azimuthal orientations fall in a grid cell. Spectral lamp radiant power, LOP, ground reflectance, ground altitude & tilt, and lamp height relative to the ground are defined independently for each grid cell. Reflection on the ground is assumed to be lambertian. It is planned to implement bidirectional reflectance functions in the future. Detailed computation of shadowing effects from masking by ground elevation is performed while a crude calculation is done for subgrid masking by smaller obstacles like trees and buildings.

2.2.2. Modeling domain

The modeling domain includes the main light sources that may have a significant effect on the MMO. In this study, we set the horizontal resolution to 1 km. This resolution has been chosen to match the worst gridded dataset to be used, namely the Defense Meteorological Satellite Program Operational Linescan System (DMSP-OLS) nighttime satellite radiances. The model boundaries have been chosen to ensure a buffer region of 50 km between the observatory and its nearest domain limit.

Given that the model height is 30 km, this means that we can accurately model zenith angles up to \(z \approx 60^\circ\). This limitation is only encountered toward the south and in this specific orientation, no significant sources are found before a distance of 100 km. Therefore, in our case, even toward the south the model calculations are accurate up to \(z \approx 75^\circ\). The domain extent is 45°N to 47.5°N and 75°W to 70°W. This domain is covered by 395 × 290, 1 km by 1 km cells. The modeling domain can be seen in Fig. 1(b).

2.2.3. Preparing input data

To perform a modeling experiment for a given spectral line, relevant gridded and non-gridded datasets have to be

Fig. 4. Light paths considered for the calculation of the artificial sky radiance in the model ILLUMINA. “o” represents the observer, “s” is a given voxel falling into the line of sight, “s” is a light source cell, and “m” are voxels intervening in the calculation of the 2nd order of scattering.
provided to the model. Gridded datasets include: (1) the light radiant power for the given wavelength; (2) the LOP; (3) the lamp height relative to the ground; (4) a digital elevation model (DEM); (5) the ground reflectance at the same wavelength; and (6) the land/water mask. The ground reflectance was taken from NASA’s Moderate Resolution Imaging Spectroradiometer (MODIS) Surface-Reflectance Product (MOD09A1, Vermote and Vermeulen 1999) [14]. For the 546 nm and 569 nm lines, we retained the MODIS Level 3 land band 4 (centered at 555 nm). The spatial resolution of the reflectance product is 500 m. Reflectance data is a combination of the 8 day L3 composite. The L3 composite contains the best possible observation during an 8-day period as selected on the basis of high observation coverage, low view angle, the absence of clouds or cloud shadow, and low aerosol loading. DEM is determined with the Shuttle Radar Topography Mission (SRTM). We used the 3’ resolution product of the SRTM V2 [15]. SRTM vertical resolution is 16 m in absolute values and 10 m in relative values. The help of a local expert was required to specify geographical zones with common lamp types and lamp spectral power distribution (SPD) mix. In fact, these parameters can change from one pixel to another, but, in such cases, the amount of information can be virtually impossible to gather and manage. MODIS surface reflectances, LOPs and DMSP-OLS upward radiances are combined using Eq. (1) to produce the light radiant power map.

$$\Phi = R_\lambda \left( \frac{I_{OLS}}{1 - \pi(1 - F_{up})} \rho + LOP(0) \right)$$

$\Phi$ is the spectral radiant power (W), $R_\lambda$ is the calibration constant for each spectral line considered, $I_{OLS}$ is the DMSP-OLS radiance (Version 4, Elvidge 2008), $F_{up}$ is the upward flux fraction, $\rho$ is the ground reflectance, and $LOP(0)$ is the value of the light output pattern toward zenith. We used the zenith angle even if we know that in many cases, DMSP-OLS is not looking toward nadir. However, we consider that this weakness of the model is mitigated by the fact that in many cases the reflected light

Fig. 5. Zoom around the OMM of the radiant power images for 2005 (left) and 2009 (right) at 546 nm ((a) and (b)) and at 569 nm ((c) and (d)).
is dominant in this equation. In a future version of our model, we plan to account for the mean viewing angle of the satellite and then use the relevant angle instead of 0. The DMSP-OLS dataset is maintained by the Earth Observation Group of the National Geophysical Data Center (NGDC) which is a part of the US National Oceanic and Atmospheric Administration (NOAA). DMSP-OLS data are coded from 0 to 63 on a linear, but relative sensitivity scale. Some pixels may be saturated and in that case are set as numerical value 63. This dataset is a yearly composite where only the cloud screened and stable values are used. To minimize the potential impact of sensitivity changes from one satellite to another, we used the data from the same DMSP satellite (satellite F16). We assume that variations in the satellite radiances from one year to another are directly linked to real ground based variations. Our use of uncalibrated data is not a limitation in this study, given the entire analysis is based on relative comparisons from one year to another.

Fig. 5 gives four examples of radiant power maps created with Eq. (1) for two spectral lines, 546 nm and 569 nm, associated to specific lamps. The 546 nm line is a mercury (Hg) line produced by MV lamps and MH lamps. The 569 nm line is a sodium line (Na) produced by HPS. The maximal radiant power in the 546 nm line appears lower than that in the 569 nm line. We can explain this by the fact that the highest installed radiant power per square kilometer occurs in cities while MV and MH lamps are more common in the countryside. According to spectral sky radiance measurements made in 2006 at the MMO by Aubé and available from the Sky spectral radiance database [16], the two lines are typically of the same magnitude. But, of course, the MMO is far from city lights and thus more dependent on countryside sources. It is easy to notice that the radiant power at 546 nm shows a significant reduction in 2009 compared to 2005 around the MMO (identified by the black star). A lower but significant reduction is also visible over the city of Sherbrooke located around coordinate 240 W–E and 50 S–N. We also observed a general increase in the installed radiant power both in the 546 nm and 569 nm lines for all other sites.

Table 1 summarizes the characteristics of the lighting infrastructure both in 2005 and 2009. In this table, it is possible to find the proportion of each lamp type for different regions. Lamps are distinguished by their mix of photometric types and their mix of spectral types. The lighting inventory was simplified to retain only the three most common photometric types. In fact, in southern Québec, most light fixtures can be associated to one of the three models shown, even if they are not exactly the same. The percentage of each photometric type was determined using Street View in Google Maps. We first chose a set of random locations inside each region (MMO, Cookshire and Lac Mégantic, Sherbrooke, and elsewhere in Québec) and then determined the number of fixtures corresponding to each photometric type present using Street View. We distinguished urban from rural environments as it is shown in Table 1. For the percentage of each spectral type, we visited each region at night to count the number of white and yellow lamps (respectively lamps emitting a 546 nm Hg line and lamps emitting a 569 nm Na line). Resultant LOPs for each region shown in Table 1 were computed by doing a linear combination of each of the three individual lamp LOPs with respect to the percentage given in Table 1’s legend.

Finally, the model requires some non gridded parameters that are considered constant over the entire geographical domain: (1) the wavelength used; (2) the aerosol optical depth (AOD); (3) the aerosol scattering and absorption cross sections at the given wavelength and relative humidity; (4) the AOD of the atmosphere and (5) the solar zenith angle. Some of these parameters are considered constant over the entire geographical domain, whereas others may change from one region to another. For example, the AOD of the atmosphere and the solar zenith angle, which is considered constant over the entire geographical domain, may change from one region to another. For example, the AOD of the atmosphere and the solar zenith angle, which is considered constant over the entire geographical domain, may change from one region to another.
the aerosol scattering phase function (aerosol model) at the given wavelength and relative humidity; (5) the ground level atmospheric pressure and the average height and distance between subgrid obstacles; (6) the observer position; and (7) the viewing angles. The values of non gridded parameters used for this study are listed in Table 2.

3. Results and discussion

3.1. Output data

ILLUMINA generates three different outputs. The first one is the artificial sky radiance calculated for a given viewing angle and observer position in a given spectral line. The model also generates two gridded outputs: the contribution map and the sensitivity map. The contribution map indicates from where and in what proportion the artificial sky radiance originates from. The sensitivity map indicates how sensitive the artificial sky radiance values are to any change in the installed radiant power at a given model cell containing at least one light device. Contribution and sensitivity maps for different sites and periods can be accessed via an interactive web portal developed and maintained by our group [17].

3.1.1. All sky radiance ratio maps

These maps illustrate changes in artificial sky brightness by taking the ratio of the artificial sky radiances observed after the light conversion project over the artificial sky radiances observed before the conversion project. Each plot is composed of 121 ratios for different viewing angles (six zenithal angles (75°, 70°, 60°, 50°, 30°, 0°) and twenty four azimuthal angles (0–345° at 15° intervals)). A single all sky radiance ratio map requires 242 model runs to be accomplished.

3.1.2. Sky radiance contribution map

The contribution maps illustrate how each square kilometer of land contributes to artificial sky brightness detected at a given viewing angle from the MMO. This map is normalized so that the sum of all pixels equals 100%. The values are expressed in term of percentage points per square kilometer.

3.1.3. Sky radiance sensitivity map

The sensitivity maps illustrate the impact on artificial sky brightness measured at the MMO of an hypothetical generic street lamp installed on each square kilometer. The sensitivity map is only calculated for pixels containing a non-zero radiant power. This map is also normalized so that the sum of all pixels equals 100%. This map is very useful for local decision-makers as it allows them to identify the places where intervention is necessary to efficiently reduce sky brightness.

3.2. Sky radiance contribution and sensitivity maps analysis

All the contribution and sensitivity maps are georeferenced and published in a web portal [17]. There is one contribution and one sensitivity map for each model configuration (121 viewing angles, five wavelengths, five aerosol optical depths, and two night periods). The maps corresponding to zenith viewing angle are reported in Figs. 6 and 7. Panes (a) and (b) in Fig. 6 show a comparison of summer zenith contribution maps before and after the creation of the Mont-Mégantic area IDSR under the same conditions (clear sky and 546 nm Hg line). Artificial sky radiance has decreased significantly around the MMO. We found a relative reduction of 50% at zenith. The replacement of MV and MH lamps to HPS Helios lamps in 2005, the zenith 546 nm Hg line radiance came mainly from closer and small towns surrounding the MMO. In 2009, the 546 nm Hg line radiance came mainly from farther. This change is clearly illustrated by the greater spread in contribution of pane (b) compared to pane (a). We have integrated all contributions from different IDSR zones and also for some nearby villages. Table 3 gives a compilation of these integrations. In zone 1 (less than 25 km from the MMO), the total contribution to the zenith 546 nm Hg line radiance in 2005 was 57.2%; this was reduced to 12.1% in 2009. In zone 2 (25 km to 50 km from the MMO), the total contribution to the zenith 546 nm Hg line radiance was 23.3% in 2005 and 45.7% in 2009. Interestingly, under clear sky, zone 3 shows a very low contribution to the 546 nm Hg line in 2005 and in 2009 (0.9% and 1.1% respectively; see Table 3). The same remark stands for the 569 nm Na line for both years (2.3% and 3.3% respectively). Despite Sherbrooke being the largest city in the region (154,000 inhabitants), it is quite far from the MMO (60 km away)

Table 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelengths (in nm)</td>
<td>436 (Hg), 498 (Na), 546 (Hg), 569 (Na), 616 (Na)</td>
</tr>
<tr>
<td>Aerosol optical depth (no units)</td>
<td>0.05, 0.1, 0.2 (low turbidity, clear sky)</td>
</tr>
<tr>
<td></td>
<td>0.5, 1 (high turbidity, hazy sky)</td>
</tr>
<tr>
<td>Aerosol model</td>
<td>Rural</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>70%</td>
</tr>
<tr>
<td>Ground level atmospheric pressure</td>
<td>101.3 kPa</td>
</tr>
<tr>
<td>Average obstacle height</td>
<td>9 m</td>
</tr>
<tr>
<td>Average distance between obstacles</td>
<td>13 m</td>
</tr>
<tr>
<td>Observer position</td>
<td>MMO</td>
</tr>
<tr>
<td>Zenith angles (degrees)</td>
<td>0, 30, 50, 60, 70, 75</td>
</tr>
<tr>
<td>Azimuthal angles (degrees)</td>
<td>0–345° at 15° intervals</td>
</tr>
</tbody>
</table>

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and, moreover, an important part of the city is masked from view by the MMO by a hill located on its eastern side.

For polluted atmosphere conditions, we observe that the contribution values are constrained around the MMO (e.g. in 2005, 95.2% of the 546 nm Hg line radiance was coming from zone 1 (see Table 3)). This is the effect of the extinction of light with distance. Basically, panes (c) and (d) of Fig. 6 are showing that under high turbidity conditions, the light coming from remote light fixtures is not contributing to the local artificial sky brightness. In other words, the artificial sky brightness is completely dominated by local sources. According to Fig. 6, we can roughly estimate that the action radius of zenith artificial sky brightness under an aerosol optical depth of 1.0 is of the order of 20 km while it can reach 50–100 km when the aerosol optical depth is 0.2.

With contribution maps, it becomes easy to associate part of the artificial sky radiance values with specific points on the ground. We are then able to identify the places that are most damaging in terms of their impact on artificial sky brightness. Our results can be used to strategically minimize the impact of light pollution on the MMO’s astronomical activities and to efficiently control the addition of new street lights in the surroundings.

In addition to the contribution maps in the 569 nm Na line (panes (a) and (b)), Fig. 7 shows the sensitivity maps (panes (c) and (d)). The highest values in these maps show where we must intervene first in order to achieve a more
efficient sky brightness reduction. Pane (c), which corresponds to 2005, clearly shows that only the conversion of sources inside zone 1 was likely to reduce sky brightness.

The map also shows that special emphasis had to be put on the sources located nearest to the MMO. In 2009, the extent of the sensitive zone had increased compared to 2005 and,

Table 3
Integrated contribution to the zenith artificial sky brightness for the International Dark Sky Reserve zones and villages.

<table>
<thead>
<tr>
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<th></th>
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</thead>
<tbody>
<tr>
<td>Zone 1 – 0–25 km</td>
<td>57.2</td>
<td>12.1</td>
<td>55.0</td>
<td>27.7</td>
<td>95.2</td>
<td>56.4</td>
</tr>
<tr>
<td>Zone 2 – 25–50 km</td>
<td>23.3</td>
<td>45.7</td>
<td>22.8</td>
<td>35.4</td>
<td>3.8</td>
<td>33.4</td>
</tr>
<tr>
<td>Zone 3 – Sherbrooke</td>
<td>0.9</td>
<td>1.1</td>
<td>2.3</td>
<td>3.3</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>Lac-Mégantic</td>
<td>4.9</td>
<td>2.9</td>
<td>4.9</td>
<td>4.7</td>
<td>1.4</td>
<td>4.0</td>
</tr>
<tr>
<td>Notre-Dame-des-Bois</td>
<td>4.1</td>
<td>0.8</td>
<td>4.0</td>
<td>2.4</td>
<td>8.9</td>
<td>8.0</td>
</tr>
<tr>
<td>La Patrie</td>
<td>4.7</td>
<td>1.0</td>
<td>4.5</td>
<td>2.9</td>
<td>7.4</td>
<td>7.1</td>
</tr>
<tr>
<td>Scotstown</td>
<td>3.2</td>
<td>0.7</td>
<td>3.1</td>
<td>2.0</td>
<td>3.0</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Fig. 7. Zoom around the Mont-Mégantic Observatory (MMO) of the summer zenith contribution and sensitivity maps for 569 nm Na line in 2005 (left) and in 2009 (right). The contribution maps are shown in panes (a) and (b) and the sensitivity maps are shown in panes (c) and (d). All panes correspond to typical summer, clear sky conditions for Québec province with an aerosol optical depth of 0.2.

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in the context of a future conversion program, efforts would have to target a larger zone with an approximate radius of 40 km. In that case also, the most important sources to check or reduce are those closest to the MMO. In a certain sense, this result is showing that during the IDSR conversion project, it was more efficient to focus on reducing the radiant power in zone 1 than making any conversions in zone 2. Here, it is important to understand that sensitivities are only computed for pixels having non-zero radiant power. This also contributes to the increased geographical extent of sensitivity from 2005 to 2009. In fact, in 2009, the extent is larger because light fixtures have been added in places where there were none in 2005.

3.3. All sky radiance ratio maps

The results for the artificial sky brightness ratio data for summer 2009 over summer 2005 are shown in Fig. 8. The results are reported for the 546 nm Hg and 569 nm Na lines under clear and hazy sky conditions. The comparison between these lines under clear sky conditions (panes (a) and (b)) shows that the reduction at the zenith for the 546 nm Hg line is about 50% compared to only about 30% for the 569 nm Na line. These results are explained by the fact that most of the MV and MH lamps were replaced by HPS lamps in the IDSR, so that the number of final HPS lamps increased. The results under a hazy sky show a zenith reduction of 90% for the 546 nm Hg line (Fig. 8(c)). This greater reduction can be explained by the fact that under hazy conditions, most of the artificial sky brightness is generated by nearby light sources and the lamp conversion initiative was implemented nearby to the MMO (mainly inside a radius of 25 km, e.g. zone 1 in Fig. 2). Even if there are no astronomical observations under hazy conditions because of the extinction of star lights, the sky appears darker after the conversion. In essence, we can say that in high turbidity conditions, the sky 546 nm Hg line radiance was \( \times 10 \) times brighter in 2005 compared to 2009.

In southern Québec, the snow cover during winter is quite significant. We decided to take this into account and performed a modeling experiment using the winter ground reflectance data given by MODIS (data extracted for February). The all sky 546 nm Hg line ratio is shown in Fig. 8(d) for clear

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![Figure 8](image.png)

**Fig. 8.** All sky maps are for ratio data for summer 2009 over summer 2005. Panes (a) and (b) are for typical clear sky conditions for Québec with an aerosol optical depth of 0.2 for Hg (546 nm) and Na (569 nm) lines, respectively. The map in pane (c) presents results for typical hazy sky conditions for Québec with an aerosol optical depth of 1.0 for the Hg line (546 nm). Pane (d) presents results for winter with typical clear conditions for Québec with an aerosol optical depth of 0.1 for the Na line (569 nm). The direction and the distance (in km) between the main towns and cities and the MMO are displayed around the map. The ratio is expressed as contour lines.

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sky conditions. The result is very interesting, as we notice that the reduction is almost constant across the entire sky, contrary to what we observed in summer where the reduction is maximal around zenith. The uniformity of the winter all sky reduction can be understood by the fact that during winter, most of the light goes up when it is reflected by the snow (given the high reflectance of the snow). Also, this reflection is almost lambertian, so that the impact of the angular dependency of the LOP become very small compared to the reflected flux. One reason to see an artificial sky brightness increase toward the horizon during summer is that LOPs often show a peak near horizontal emission and this near horizon light is traveling large distances. During the summer, the lambertian angular dependencies of the reflection are less important with respect to the global angular emission of a ground element (direct light and reflected light) because of the low reflectance of the ground. In winter, the reflection becomes predominant so that the near horizon emission of light is relatively less important, subsequently decreasing the zenith to horizon variation in artificial sky brightness.

In the North–West direction during summer (Fig. 8(a)), toward the small village of Scotstown located at 12 km from the MMO, we observed an artificial sky brightness reduction as low as 5% for the 546 nm Hg line and almost 0% for the 569 nm Na line. The lighting conversion efforts in that village were not very successful in reducing sky brightness at that viewing angle. This low reduction can be understood by the fact that, at that angle, an important part of the sky 546 nm Hg line radiance is coming from zone 2, more specifically, around the Graymont mine near Bishopton and around the village of Weedon. In Table 4 we can see that in 2005, 29.8% of the 546 nm Hg line radiance was coming from zone 2 while 23.9% was coming from zone 1. This higher contribution of zone 2 is even more marked than in 2009 (5.2% and 36.7%, respectively). One reason is that the level of artificial sky brightness in the 546 nm Hg line came to be comparable to 1979 levels. For the 569 nm Na line, the target of reducing by 50% was not reached, but the reduction is nevertheless significant.

The contribution to the sky radiance from large and distant cities is lower than expected. In 2003 [7], it was estimated that Sherbrooke was contributing up to ~25% of the artificial sky brightness experienced by the MMO, but our study suggests that, in 2005, it was of the order of 1% at zenith. On the other hand, the 2003 estimates for zones 1 (25 km radius from the MMO) and 2 (25 km to 50 km from the MMO) were quite accurate, 50% for zone 1 and 25% for zone 2, respectively, whereas we report ~56% for zone 1 and ~23% for zone 2, on average for the two lines.

Our results also highlight critical zones where a change in the lighting infrastructure is likely to have a more significant impact on sky brightness at the MMO. The contribution and sensitivity maps developed are useful cartographic tools to help authorities manage their lighting infrastructure in such a way to reduce sky brightness and its adverse effects. The results have been shared with MMO officials and are being used as a tool to improve sky quality at the observatory.

In 2011, the ASTROLab had to re-launch its light pollution abatement project in order to curb the installation of non-compliant light fixtures, which deteriorate the quality of the night sky and may endanger the sustainability of the reserve. The recent massive introduction of Light-Emitting Diodes (LED), with all of their advantages and disadvantages, represents a major new challenge for the ISDR to tackle. Projects are currently underway to investigate and monitor this type of lighting, as well as to limit its potential contribution to sky brightness. Our modeling approach can be adapted to do further research on this topic to determine whether there are grounds for restricting LED street light installation.

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