

Article

Evaluating the potential health impact of obtrusive light: Application to Montréal, Canada

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Abstract: This paper describes the use of a new obtrusive light module of the Illumina v2 model to estimate the light that may enter bedroom windows. We used as input to the model, 1- the sources' flux and spectrum derived from the color images taken by astronauts from the international space station, 2- an association between source spectrum and angular emission, and 3- a per zone inventory of obstacles properties and lamp height. The model calculate the spectral irradiance incident to buildings' windows taking into account for the orientation of the street. By using the color information from an ISS image, we can classify pixels as a function of their spectra. With the same image, it is also possible to determine the upward photopic radiance for each pixel. Both serve as inputs to the model to calculate the spectral irradiance on any window. By having the spectral irradiance, it is possible to determine the Melatonin Suppression Index and the photopic irradiance on the window. Such information can later be used to perform epidemiological studies. The new methodology is applied to the case of Montréal in Canada for a set of houses' locations. The computations are made for 2013 (pre-LED era).

Keywords: human health, light pollution, modeling, street light, Montréal, melatonin suppression, obtrusive light

1. Introduction

Innovations in the field of lighting have shaped the history of the last century. Due to their numerous uses, our society has become light dependent. As any other innovation, lighting technologies come with their advantages and disadvantages. The negative aspects of these technologies seem to be unknown by most people. The unexpected effects of what is now called Artificial Light At Night (ALAN) have first been mentioned by astronomers. Within the past decade, multidisciplinary researchers became aware of the actual issues. Indeed, abnormal behaviours have been observed among several nocturnal species [1] due to ALAN. Negative impacts on bats [2], turtles [3], fish [4] and songbirds [5] have already been identified. Moreover, it is now known that ALAN does have an effect on plants [6–10]. On the other hand, what seems even more concerning is the possible impacts of ALAN on human health. For humans, the first suspected impacts are related to breast and prostate cancers [11–13]. ALAN plays a role in disturbing circadian rhythm [14], even in low intensity lighting [15]. The disturbance in the circadian cycle also plays a role in the increase of obesity [16]. In order to provide a reference to establish the potential impact of a given spectrum of ALAN on the melatonin suppression, Aubé *et al.* 2013 introduced the Melatonin Suppression Index (MSI). Since its introduction, some studies verified if associations exist between the MSI and a variety of diseases. Among them, Garcia-Saenz *et al.* [18] and Garcia-Saenz *et al.* [19] found that, for Spanish cities, regions with high MSI, are associated with increased risk of breast, prostate and colorectal cancers.

The goal of this paper is to present a new methodology combining color remote sensing of the lighting technologies with a radiative transfer model to determine the spectral irradiance falling on a

window facing a street at any location. We will show how such a method can provide new information compared to using spaceborne images solely. The method is firstly applied to the Montréal's lighting infrastructure as it was in 2013, before the massive street light conversion to Light-Emitting Diodes (LED).

2. Modeling approaches

Over the past decades, models have been designed in order to reach a common goal: modeling the sky brightness for a given area. The first numerical model has been designed by R.H. Garstang in the 1980s [20]. Compared to the most recent models, it was relatively simplistic. In fact, the angular light output pattern (LOP) was prescribed and needed to be uniform everywhere. Furthermore, the cities were circular with constant lumen per square kilometer, and had no topography. The main advantage of Garstang model was based on its simplicity, speedy calculations and on the ease of producing model inputs. Later on, Luginbuhl *et al.* [21] and Cinzano and Falchi [22] improved the Garstang's model allowing each pixel to be considered as a circular lighted surface. By combining a certain number of pixels, they could consider cities of any shapes. Different LOPs were suggested, some including a correction to mimic the screening effects of obstacles such as trees and buildings. More advanced models were proposed by Aubé *et al.* [23] and Kocifaj [24]. They are involving the resolution of the radiative transfer in more complex environments. Illumina v0 model [23] makes it possible to include subgrid obstacles, variable aerosols, and a pixel-based light source inventory with variable spectra and LOP. From the beginning, Illumina incorporates the 2nd order of scattering. Illumina is extremely heavy and ideally requires access to a supercomputer [25]. Illumina was significantly upgraded in 2018 [26] and in 2021 [27] by including a full hyperspectral support, improved subgrid obstacle blocking, improved resolution (tested down to 20 m), multiple aerosol layers including fog and dust, overhead clouds, and the calculation of the direct radiance and irradiance (from sources and reflecting surfaces). The latest available version is v2 [28].

All the above-mentioned models were initially designed with the aim of characterizing the impact of the light pollution on the star visibility for astronomical purposes. When it comes to estimate the effect of the light pollution on human health, one must first consider that the most affected areas are likely concentrated inside cities. Unlike what happens in the countryside, the light pollution field in cities is clearly dominated by the light coming directly from the lighting devices without interfering significantly with the atmosphere. That light may enter buildings' and houses' windows directly and after reflection on nearby surfaces. To allow the estimation of the obtrusive direct light, a new module has been added to the Illumina in its version v2. Illumina v2 model throws a set of photons from each individual light source and then reaches the observer's field of view. The model considers six different paths borrowed by the photons. Those include two single scattering, two second order scattering and two direct light paths. When it is time to determine the obtrusive light in a city, the last two paths are the most significant. There are many modeling parameters defined independently for each grid cell such as the radiant spectral flux, the LOPs, the ground reflectance, the ground altitude, the lamp's height relative to the ground and the subgrid obstacle characteristics [26,27,29,30]. According to this set of input data, the spectral and angular characteristics of the lamps' infrastructure can be defined in the model. Used jointly with the orientation of the nearby street, one can determine the amount of light falling on the surface of a window if we assume a window facing the street on a vertical facade parallel to the street. That amount of light is dominated by two main paths: 1- the direct path from the light fixture, and 2- the light coming after the diffuse reflection on the ground or even buildings (when using resolution of the order of a meter or better). For a typical summer ground reflectance, the obtrusive light on the window that is coming after reflection on the ground is of the order of $1/10^{th}$ of the obtrusive light coming directly from the light sources while the obtrusive light coming back to the window after reflection on the opposite buildings' facades represents only a few $1/100^{th}$ of the obtrusive direct light. For that reason, we do not need to use very high resolution as a way to account

for reflection on buildings. However, when the ground is covered with fresh snow, the reflection on the ground can rise up to the same order of magnitude as the obtrusive direct light.

3. Modeling domain and period

Throughout this modeling experiment, we used a resolution of 8.5 m which is more or less the resolution of the ISS image used to determine the lamp inventory. For that experiment, we consider the position of each house’s window where we want to find the obtrusive light as a new virtual observer. Illumina v2 considers each virtual observer as a different model run and always locates the virtual observer in the center of the modeling domain. In this experiment, we used two layers having a size of 25 x 25 pixels. The first layer at a resolution of 8.5 m (201 x 210 m) and the second at a resolution of 21.25 m (531 x 531 m). This is large enough because we do not want to calculate the contribution of the light scattered by the sky that is considered negligible. One advantage of such a configuration is the rapidity of execution of Illumina v2.

Montréal is the second-biggest city in Canada, and an urban agglomeration of approximately 4 million citizens in 2014 [31]. The city has a population density of 4 438.7 citizens per square kilometre [32]. Overall, the agglomeration has a surface of 499.1 square kilometers of which 365.2 square kilometers is representing the city itself [33]. As for the topography, it is relatively flat, except for a small hill named Mont Royal. The city contains more than forty skyscrapers higher than one hundred meters [34] and the overall building density is high. It is as well frequent to see trees positioned near street lamps, blocking a part of the emitted light during summer.

Before the massive conversion to LED starting in 2017, Montréal has a street lighting mainly composed of High-Pressure Sodium (HPS) and Metal Halides (MH) lamps. The street lights photometry of HPS was mainly assimilated to a \approx 50-50 mix of cobrahead-like and helios-like light fixtures with respectively \approx 5% and \approx 1% of the Upward Light Output Ratio (ULOR). Such a mix results in a 2% ULOR on average. Most MH lamps were cobrahead-like \approx 5% ULOR. Some private lights are assumed to be mainly composed of Compact Fluorescent lamps (CFL) with a 15% ULOR. This information is summarized in Table 1. The modeling experiment presented hereby only considers the light sources extracted from an ISS image (see Figure 1). This image covers a surface of about 850 km². All sources falling outside this surface are not considered in our modeling experiment. This is not a problem since we are concerned about the obtrusive light coming from inside a radius of a few hundreds of meters. If one is concerned about the obtrusive light coming from the sky, Simoneau *et al.* [35] showed that about 90% comes from within 10 km but that situation is not considered in this study.

Table 1. Light fixtures characteristics per spectral class. The Correlated Color Temperature (CCT) and MSI are also given for each spectrum.

Class	Technology	ULOR	CCT	MSI
		%	K	
1	Metal Halide	5	4700	0.58
2	Metal Halide	5	3200	0.44
3	Compact Fluorescent Lamp	15	3000	0.26
4	High-Pressure Sodium	2	1940	0.08
5	High-Pressure Sodium	2	2010	0.12
6	Low Pressure Sodium	0	1750	0.02

4. Modeling parameters

In order to achieve the modeling, a few parameters need to be determined. Those parameters are used as the base information for the model to be executed. We chose year 2013 as a reference period for the pre-conversion to LED lighting. The datasets can be divided into two main types, namely the

uniform parameters and the gridded parameters. Those last ones are the parameters that may vary throughout the modeling domain.

4.1. Uniform parameters

The first parameter used in the model is the relative humidity. The relevance of this parameter is related to the fact that many aerosols are hydrophilic and consequently their properties, such as their size and their refractive index, are influenced by it. To determine the value that we used for the modeling, we took the average humidity that has been recorded during early 2010s for Montréal City, which is approximately 79.1%, and rounded it to 80 % [36].

Using the same methodology as above, the average atmospheric pressure for Montréal City has been set for the model as 101.1 kPa [36]. This parameter has an influence over the density of molecules present in the modeling domain, thus affecting their interactions with photons.

Other parameters considered to be uniform over the whole domain are the aerosol optical depth and the Ångström coefficient which are linked to the aerosol density and the size distribution. For this modeling experiment, we used the data available on the aerosol robotic network (AERONET) website [37]. More precisely, the data used, both for the Ångström coefficient and the aerosol optical depth (AOD), is the level 2 daily average values recorded on April 8, 2013 at the closest AERONET site (CARTEL). AOD average values are indexed according to the wavelength. We selected the AOD relative to a wavelength of 500 nm, while the Ångström coefficient is the one recorded for wavelengths 440 nm and 870 nm. A primordial parameter is the ground reflectance. We assumed a mix of 90% asphalt and 10% vegetation to be representative. Table 2 shows the values of each uniform all over the domain parameter used for the modeling.

Table 2. Uniform all over the domain input parameters used for the modeling

Parameter	Value(s)	Units
Relative humidity	80.0	%
Atmospheric pressure	101.1	kPa
Aerosol optical depth	0.15	-
Ångström coefficient	1.52	-
Aerosol model	urban	-
Aerosol profile scale height	2	km
Clouds	None	-
Additional particle layer	None	-
Surface reflectance	10% grass & 90% asphalt	%
Wavelength bins	10	
Wavelength bins width	50	nm
Starting wavelength	350	nm

4.2. Gridded parameters

The first non-uniform over the whole domain parameter that is required is the digital elevation model (DEM). This parameter, which is basically the topography of the modeling domain, is obtained from the Shuttle Radar Topography Mission (SRTM) [38]. The absolute accuracy concerning the vertical altitude is of 16 meters, while the accuracy of the relative height between two ground elements is of 10 meters. The horizontal resolution is about 30 meters.

4.3. Lamp flux and spectral type from ISS images

The upward ISS photopic radiance and the lamp spectrum classification come from the ISS night images [39]. We used the ISS035-E-17088 image taken during the ISS035 mission with the Nikon D3S Camera (400mm lens) on April 6, 2013 (Figure 1). We used pre-processed images provided by NOKTOsat [40], from which we developed a filtering process to remove the natural background

radiance and the noisy signal over unlit surfaces. This allowed to limit the number of light-emitting pixels to the significant ones. Figure 4 summarizes the steps undertaken in order to obtain filtered ISS images.

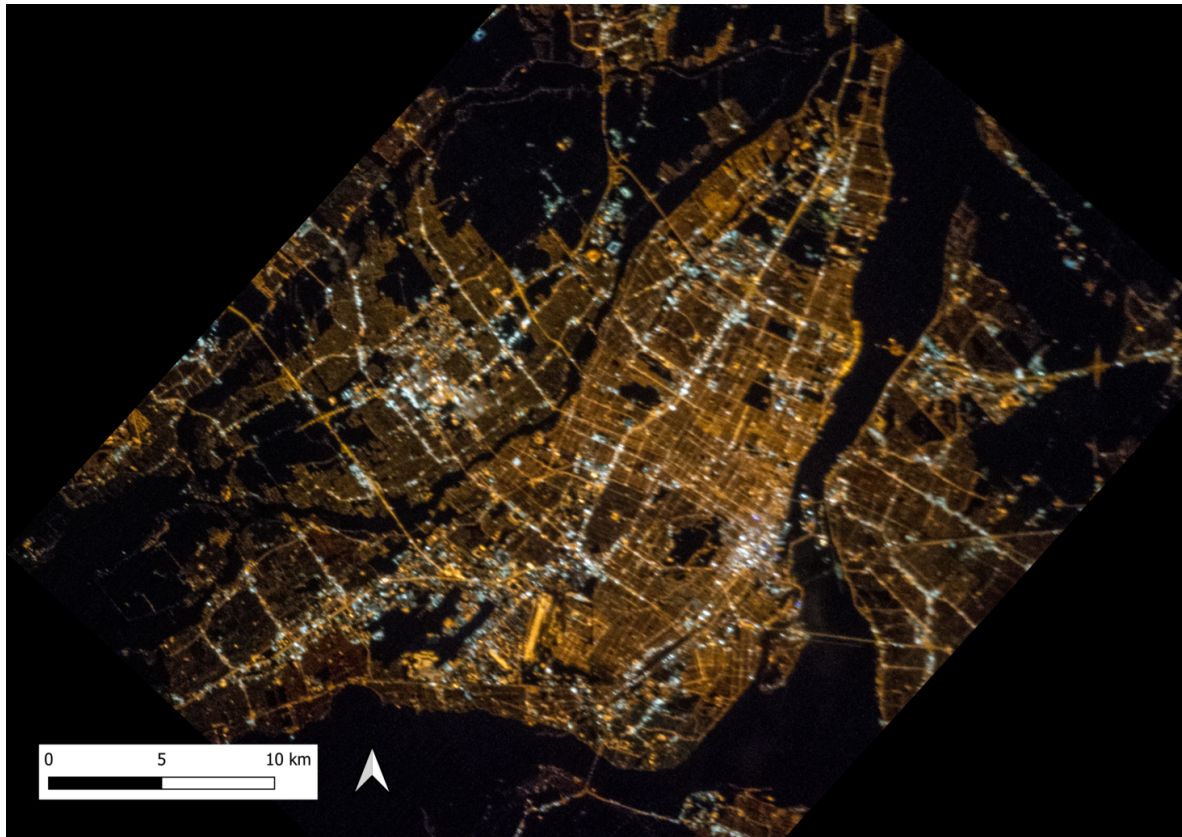


Figure 1. Georeferenced image of Montréal from the ISS taken on April 6, 2013.

As a starting point, we had access to images conveying information on the photopic radiance (image ImpactVIG_GR from NOKTOsat) as well as the lighting technologies used throughout Montréal (image Composite from NOKTOsat). As for the second image, the technologies were separated into 5 different classes: number 1 relating to cool white sources (MH or LED higher than 4000 K), number 2 to warm white sources (CFL or MH between 3000 K and 4000 K), number 3 to a mix of 3000 K fluorescent, HPS, MH or white sources between 2400 K and 3000 K, number 4 to phosphor converted (PC) Amber LED and warm HPS, and number 5 to normal HPS. A sixth category representing Low Pressure Sodium (LPS) and pure amber LED is normally included in the image provided by NOKTOsat, but this category has not been detected in Montréal. There are very few pixels belonging to class number 3. Table 1 shows the choice of technology that we have made to meet the above classes in accordance to what was available in the city in 2013.

When looking at the photopic radiance image, it became apparent that there was some background lighting present in the image. This can be explained by the reflection of starlight, moonlight and artificial sky glow on the surfaces along with the upward scattering of ground based lights. Indeed, the images revealed the presence of light in areas where there should not be anthropogenic light emitted at all (such as empty fields or bodies of water). In order to consider only artificial light emissions, we estimated the value of this background light and subtracted it from the value of every pixel in the image. This background was determined by a statistical analysis of the image. At first, a temporary image containing only the pixels of lesser value was created. As points of higher emission intensity had been eliminated, only light emissions in dark areas remained. We then analyzed this remaining data and estimated that the addition of the mode and the standard deviation of this new image would be a good value for the background removal. Indeed, the background light is quite similar throughout

the territory. It is therefore a logical assumption that the value of the background light is the most common value in the image. The standard deviation was also added to the background in order to completely eliminate the background light that could be somewhat higher than the mode in certain areas. The use of the standard deviation in the determination of the background was decided by trial and error. This empirical value fits well for the territory of study but might have to be changed when studying a different one with the same method.

Within this filtered image, isolated non-null pixels could still be found within areas that should not emit light. As to not consider these false light sources, this noise had to be eliminated from the data. A binary image was created in which the pixels were given a new value of 1 for non-null pixels and 0 for null pixels. A convolution was then applied to this binary image : a sliding window of 3 pixels by 3 pixels would consider the surrounding pixels of each individual pixel in order to determine if it needed to be eliminated. If a non-null pixel had 4 or more pixels of value 1 surrounding it (meaning that this pixel was not isolated within a dark area), it would remain of the value 1. If it had 3 or less pixels of value 1 in the sliding window, it would be given a new value of 0. This process resulted in a new binary image in which only the pixels that should realistically have a significant value were kept (the others having been converted to zeros). Finally, this binary image was multiplied to both the photopic radiance and the lighting technology images in order to obtain clean images (see Figures 2 and 3).

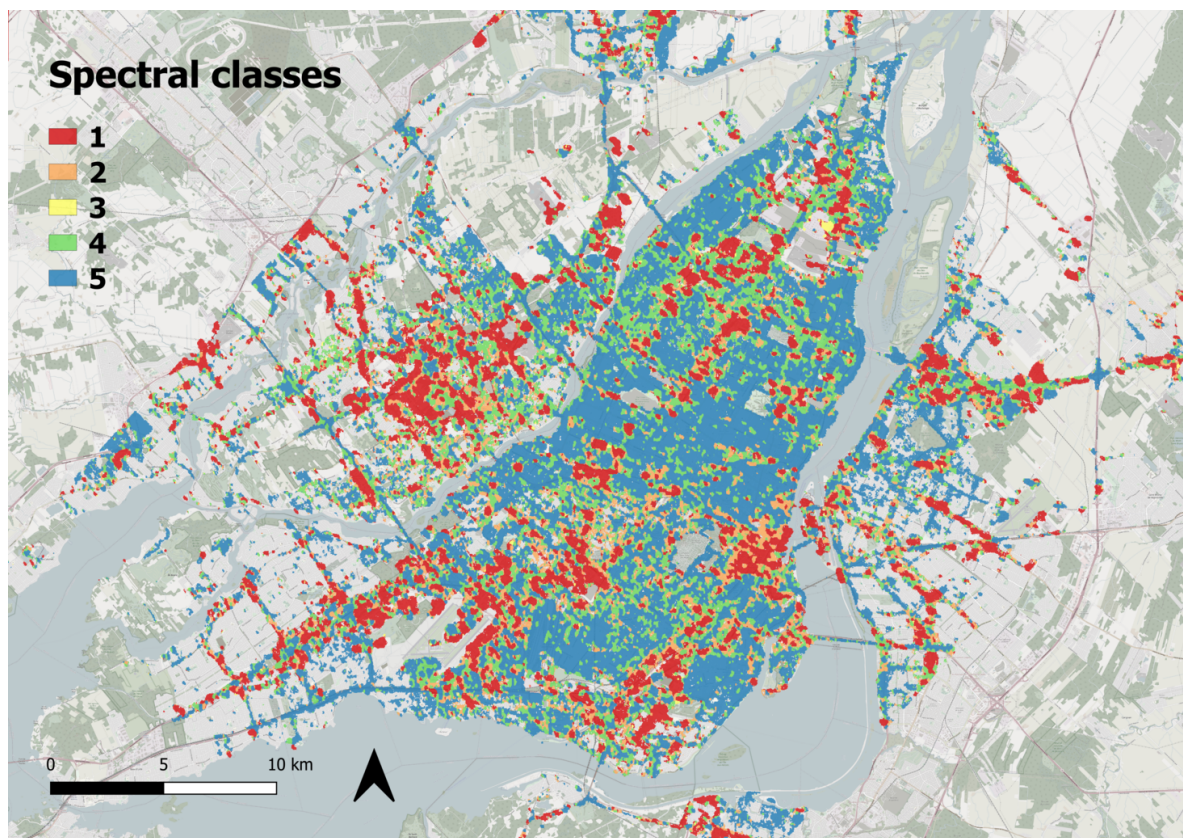


Figure 2. Filtered spectral classes image of Montréal from the ISS taken on April 6, 2013.

Afterwards, we created an image of the MSI throughout Montréal from the information contained in the filtered lighting technology image (Figure 2). We estimated the MSI for each of the 5 categories of technology present in Montréal in 2013 (Table 1). We used the data on Lamp Spectral Power Distribution Database (LSPDD) [41] to find the relevant lamp and determined the associated MSI for each spectral class. We created a lookup table associating the MSI to its class. Finally, we substituted the value relating to the class for the value of the MSI in the image (Table 1). The resulting image therefore presents the MSI for each pixel.

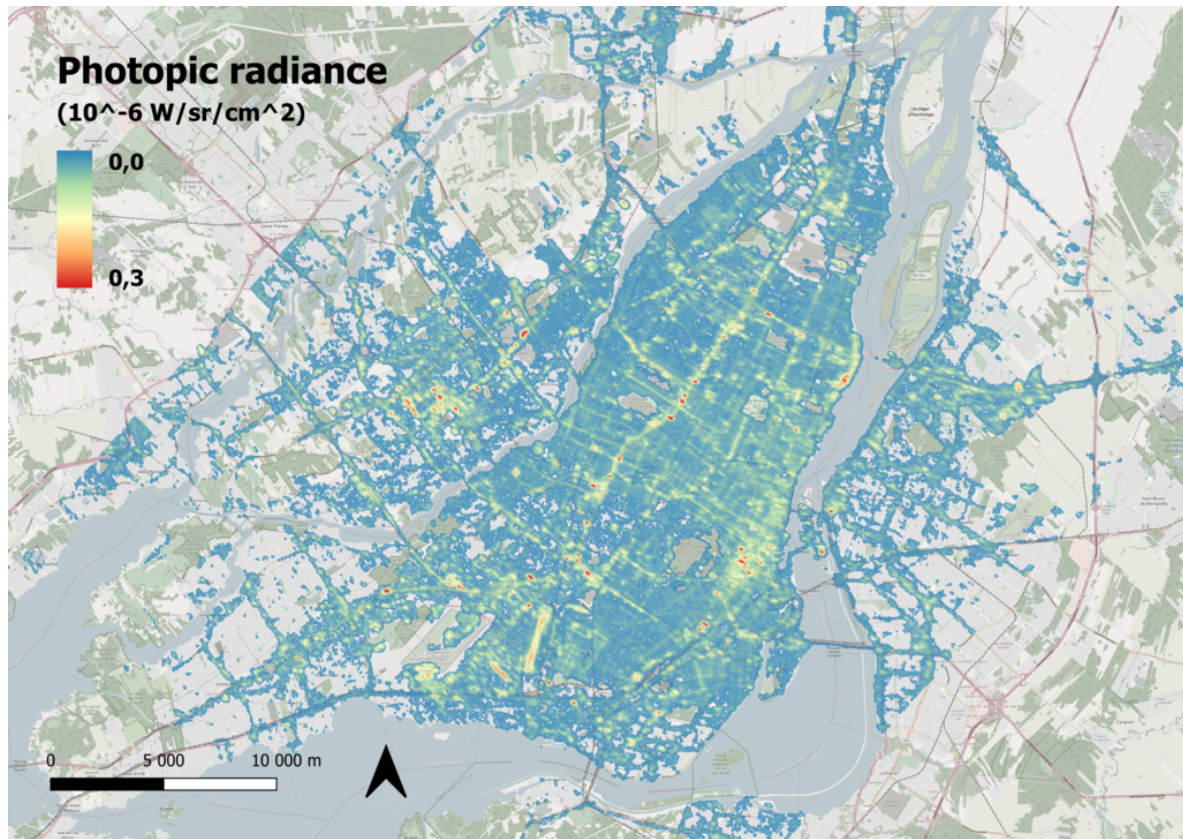


Figure 3. Filtered photopic radiance image of Montréal from the ISS taken on April 6, 2013.

4.4. Obstacle properties and lamps heights

The average height of street lamps and properties of the obstacles for each region are determined using Google Maps StreetView [42] and Google Earth [43]. A total of 309 circular zones with various radius and specific central coordinates have been defined with Map Developers [44] in order to cover the entire surface of Montréal. These zones were established according to the relative uniformity of the buildings' size, the distance between them, the lamps' height over the area and the obstacle filling factor. The procedure established to collect the required information is the same for each zone.

The first parameter defined for each zone is the average building height (h_o). This obstacle height was measured using the Path3D function in Google Earth. The average street lamp height (h_L) was also estimated for each zone using the same method. Then, the distance between the obstacles (d_o) (buildings, trees) was determined by using the ruler tool in Google Earth at an angle of $\sim 45^\circ$ from the street orientation. Although the closest obstacles would usually be in front or behind the street lamps, we considered that street lamps are engineered to direct light slightly in front of them but mostly in the direction of the street. Thus, we estimated that the average distance a photon could travel before colliding with an obstacle would be approximately equivalent to the distance of the first obstacle met at an angle of 45 degrees. We finally determined the obstacle filling factor (F). This obstacle property is a ratio out of one corresponding to the peripheral angle of a position where the path of the photons is blocked. For instance, an obstacle filling factor of 0.5 is attributed to a position if $\sim 180^\circ$ out of the total 360° are blocking light trespass.

Table A1 summarizes the various zones defined to characterize the obstacles and lamp heights. In Illumina, the order in which the zones are provided to the model is related to their priority (a new zone having a higher priority over the previous). In case of an intersection between zones, the latest zone overwrites the previous one. In Table A1, the zone number 1, established as the set of default

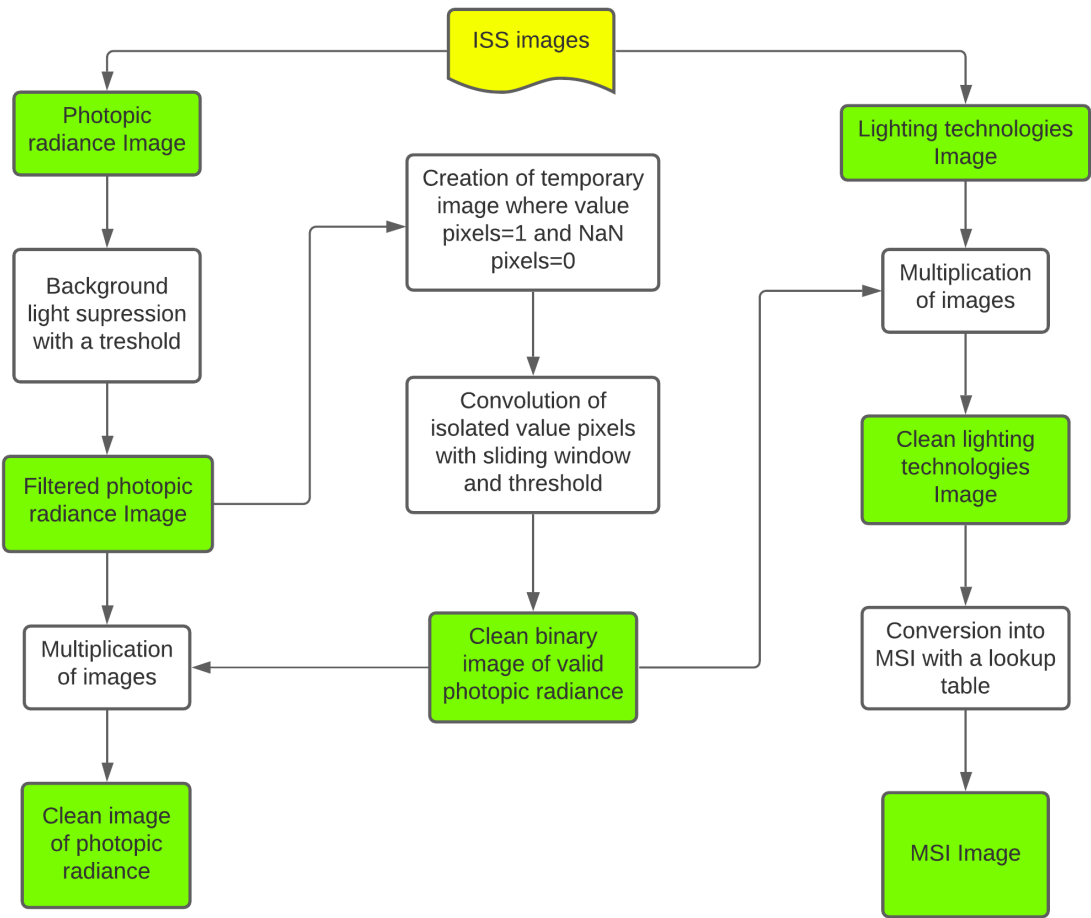


Figure 4. Organizational chart of steps undertaken to remove the background radiance and noise from the ISS images.

values, is valid for regions where no other circular zone is defined (since any zone superimposed on the first predominates).

4.5. Generic light output patterns and spectra

We considered 3 different ULORs which are 2%, 5%, and 15%. The cobrahead-like LOP (5% ULOR) was taken from the Illuminating Engineering Society of North America (IESNA) file for the Cooper’s cobrahead model. This LOP was systematically associated to MH lamps. The HPS LOPs are typically in relatively equal number of cobrahead (5% ULOR) and of Helios models (1% ULOR). The average of their IESNA files gives a new LOP with 2% ULOR. For the CFL, we assumed a LOP having 15% ULOR. In the latter case, the LOP was measured by ourselves with a farm lantern (model Globe PL-8120).

We used five different lamp spectra which were taken from the LSPDD. Figure 6 shows the spectra of the lamps used for this experiment. The associations between the spectra and the LOPs are given in Table 1.

For each pixel, we determine the spectrum and its radiant flux Φ_e . This is done thanks to the ISS derived spectral classes and upward ISS photopic radiance images. Knowing the typical LOP and spectrum associated to each pixel according to its spectral class (see Table 1), one can convert the ISS derived photopic radiance into spectral flux of the pixel (in Watt). This is done with equation 1.



Figure 5. Map of the 309 zones established for the characterization of the lamps height and obstacles properties in Montréal. The complete characteristics of each zone is given in Table A1.

$$\Phi_e = \frac{L_{e,\Omega}(\theta) \times S}{\int_{\lambda} V(\lambda) T(\lambda) \left(\frac{1}{\pi} \rho(\lambda) F_{90-180}(\lambda) + \bar{G}(\theta, \lambda) \right) d\lambda} \quad (1)$$

$L_{e,\Omega}(\theta)$ is the photopic radiance given by the ISS image Impact_VIG_GR (in units of $\text{nw sr}^{-1} \text{cm}^{-2} \text{\AA}^{-1}$) multiplied by the nominal photopic bandwidth ($\sim 1000 \text{\AA}$). S is the area of the pixel in cm^2 (which is $722\,500 \text{ cm}^2$ for a pixel of 8.5 m). $V(\lambda)$ is the spectral sensitivity of the photopic band. θ is the zenith angle between the image center and the ISS (31° in our case). $\rho(\lambda)$ is the ground reflectance. $F_{90-180}(\lambda)$ (see equation 2), and $\bar{G}(\theta, \lambda)$ are respectively the amount of light going down per unit of wavelength, and the LOP value at any wavelength for the zenith angle $z = \theta$. $T(\lambda)$ is the atmospheric transmittance but that factor has been already corrected by NOKTOSat so that we set its value to 1.

$$F_{90-180}(\lambda) = \int_{z=\frac{\pi}{2}}^{\pi} 2\pi \sin(z) \bar{G}(z, \lambda) dz \quad (2)$$

According to [26], the spectral intensity $I_{e,\Omega}(z, \lambda)$, in $[\text{W}/\text{sr}/\text{nm}]$, leaving the light source pixel at any zenith angle z is given by equation 3.

$$I_{e,\Omega}(z, \lambda) = \bar{G}(z, \lambda) \Phi_e \quad (3)$$

The radiant flux of a pixel Φ_e , in $[\text{W}]$, is determined from the ISS photopic radiance image and equation 1 combined with: 1- information from the pixel net LOP and spectrum, 2- the photopic spectral response and 3- the ground spectral reflectance [26]. $\bar{G}(z, \lambda)$, in $[\text{Wsr}^{-1}\text{nm}^{-1}]$, is the light radiation pattern of a pixel. This function gives the relative amount of light emitted at any zenith angle and any wavelength per unit of solid angle. In Illumina's usual configuration, where we get the radiance from VIIRS-DNB, $\bar{G}(z, \lambda)$ of a given pixel is a combination of different street lamps having

different LOPs and different spectra because of the large size of the pixel footprint. In the present adaptation to the higher-resolution data from ISS images, the LOP of a pixel is the same for any wavelength since we assume that only one light fixture falls inside a pixel (i.e. $\bar{G}(z, \lambda) = \bar{G}(z)$).

4.6. Determining the window orientation

Determining the angle and orientation between the window and the street lamps is crucial to model the irradiance entering in a home. We assume a window facing the closest street so that the front of the house is parallel to the street. With the objective of making our modeling approach as general as possible, we developed a numerical method to determine from any address in the world, the closest driving street. This is done by using OpenStreetMap data and an r-tree integrated in the OSMnx python library to calculate the minimal euclidean distances between points [45]. The library is also used as a tool to fragment into straight lines each small street segments. This allows obtaining the bearing angle of a segment even in curved streets. We then add the appropriate angle to get a right angle between the street and the window. This angle is then used as an input value to the Illumina model (the azimuth viewing angle). For the elevation viewing angles, we aim to determine the irradiance on the vertical surface of a window. So that the elevation angle is always equal to zero. Figure 7 shows the resulting angles for a small part of Montréal.

5. Results for some Montréal sites in 2013

In order to test and compare our modeling and remote sensing methodologies, we identified five different sites across the modeling domain. They are differing by their urban zoning categories. We actually selected a site in the city center, another in an urban residential area, one in a suburb residential area, plus one in a commercial area and finally another in a rural area. Each site differ by their distances between buildings and buildings’ heights. All precise locations are on a building facade facing the street. We defined up to three floors but for some sites only one or two were kept with respect to the actual height of the buildings. We used 2, 5, 8 m above ground as the default set of heights. Detailed information about the sites is shown in Table 3.

Table 3. List of modelled sites

#	Environment	Window height m	Latitude deg	Longitude deg	d_o	h_o	F	h_L
1	City center	2, 5, 8	45.501171	-73.565357	30	100	0.96	9
2	Urban residential	2, 5	45.488376	-73.596217	37	12	0,93	8.5
3	Suburb residential	2	45.533026	-73.703789	40	11	0,93	8
4	Commercial	2, 5, 8	45.468995	-73.542072	55	9	0.89	9.5
5	Rural	2, 5	45.642133	-73.662191	0	0	0	7.5

Table 4 shows the comparative results obtained with the two methods to estimate both the MSI and the amount of photopic light for the five sites. One can notice that for MSI, no significant variation occur according to the window height (Illumina MSI). On the other hand, the Illumina photopic irradiance decreases with the window height. There is no obvious link between the Illumina MSI and the upward ISS MSI. The same observation arises with the comparison of upward ISS photopic radiance and the Illumina photopic irradiance.

In order to better explore if the ISS derived parameters are somehow correlated to the equivalent parameters determined with Illumina v2, we decided to select 500 sampling points across the city. The 500 points locations are shown in Figure 8. If no significant new information is provided by Illumina v2 compared to the one derived from the ISS images, we should observe a relatively good correlation between the values obtained directly from the ISS images and the Illumina v2 derived values. Figure 9 shows scatter plots between the ISS images derived values and their equivalent from Illumina v2. The figures clearly show that the datasets are lowly correlated. That means that Illumina

v2 provides significant new information compared to the ISS derived parameters. For that reason such modeling results can represent an advantage over direct remote sensing techniques when it comes to verify if there is any associations between the ALAN and health issues. Figure 9 also shows that the correlation coefficient between the ISS MSI and Illumina v2 do not significantly change according to the window height. This result is consistent with the fact that for our five sites, no significant changes were observed with various window height. One can notice that, for the MSI correlations, the density of points is higher around the 1:1 relationship and that Illumina generally predict higher MSI for low ISS MSI values and lower MSI for high ISS MSI values (see panels (a), (b) and (c) of Figure 9). This is normal because the Illumina MSI does not only involve the pixel's lamp but also the nearby ones so that Illumina provides a sort of complex averaging effect on the MSI. However, the relationship between the upward ISS photopic radiance and the Illumina photopic irradiance shows a decreasing correlation with higher window height.

Figure 10 shows the irradiance spectra obtained with Illumina v2 for the 5 sites for windows 2 m above ground. We only provided them for 2 m because almost no changes were observed in the spectra shapes with higher window height. It is also clear that the spectrum is highly sensitive to the site location and the respective mix of lamp spectra located around each location. One nice aspect of using Illumina v2 is that it provides spectra. Having spectra allows a verification of any other lighting parameter, not only the MSI. As an example, one can calculate the CCT. Another interesting possibility provided by the model is to determine the photoreceptor response to the given irradiance by humans or any other animal specie. Illumina v2 also calculates the radiance spectra in a specific direction so that it can be useful when the direction of the light is of some importance. We did not use that feature in the present study.

Table 4. Comparative results for the identified sites. Illumina MSI and Illumina photopic irradiance are the results obtained with Illumina v2 while ISS MSI and ISS photopic radiance are the values derived from the ISS images.

#	Environment	Illumina height m	ISS MSI	Illumina MSI	ISS photopic radiance $\mu\text{W sr}^{-1} \text{cm}^{-2}$	Illumina photopic irradiance W m^{-2}
1	City center	2	0.43	0.44	0.0442	5.91×10^{-3}
		5		0.44		5.47×10^{-3}
		8		0.44		3.18×10^{-3}
2	Urban residential	2	0.08	0.15	0.0135	1.59×10^{-4}
		5		0.14		1.38×10^{-4}
3	Suburb residential	2	0.12	0.14	0.0128	7.51×10^{-5}
4	Commercial	2	0.62	0.53	0.0511	1.03×10^{-4}
		5		0.53		9.52×10^{-5}
		8		0.53		9.14×10^{-5}
5	Rural	2	0.12	0.14	0.0037	5.08×10^{-5}
		5		0.14		2.17×10^{-5}

6. Conclusion

The goal of this paper was to present a new methodology combining color remote sensing of the lighting technologies with the radiative transfer model Illumina v2 to determine the spectral irradiance falling on a window surface facing a street at any location. By using the numerical model Illumina v2, we were able to establish that no clear correlation exists between the model results and the MSI and photopic radiances derived with the ISS images. The low correlation may indicate that Illumina v2 provides new information that is not available from the ISS images. We think that this result highlights that the use of Illumina v2 is promising to perform epidemiological studies related to the color and amount of obtrusive light. For that reason, we aim to provide such information to researchers in

the field of epidemiology in order to verify if any association can be found between the Illumina v2 derived obtrusive light parameters and human health issues.

One other interesting result is that the Melatonin Suppression Index is almost insensitive to the window height while the spectral irradiance decrease with the window height. Moreover, the correlation between the ISS derived radiances and the Illumina v2 irradiances is worse for higher window heights. The reduction of the irradiance with height combined with the constant MSI is interesting to disentangle the effect of the spectral content versus the amount of light.

In the future, we plan to perform an in situ validation experiment in Montréal in order to determine the accuracy of the modelled approach presented here. That experiment will require the measurement of the irradiance on a set of sites for which we computed the Illumina v2 irradiance spectra. We are expecting to perform that experiment with the LANcube radiometer [46] in the coming year.

Author Contributions: We applied the sequence-determines-credit approach [47] for the sequence of authors which is in order of decreasing contributions. Conceptualization, M.A. ; methodology, M.A. , J.-P.H., J.D., N.V., É.B. ; software, M.A. , J.-P.H., J.D., N.V., É.B.; validation, M.A.; formal analysis, M.A.; investigation, M.A. , J.-P.H., J.D., N.V., É.B.; resources, M.A.; data curation, M.A.; writing–original draft preparation, M.A. , J.-P.H., J.D., N.V., É.B.; writing–review and editing, M.A. , J.-P.H., J.D., N.V., É.B.; visualization, M.A. , J.-P.H., J.D.; supervision, M.A.; project administration, M.A.; funding acquisition, M.A.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Montréal’s obstacle and lamp height inventory

Table A1. Fitted parameters for the various winter cases modelled in this paper.

Zone	Latitude deg	Longitude deg	Radius m	d_o m	h_o m	F	h_L m
1	45.557810	-73.672506	30650.92	0	0	0	7.5
2	45.494639	-73.899268	4121.07	80	15	1	0
3	45.49488	-73.867339	1948.43	35	11	0.93	4.5
4	45.508456	-73.90757	1142.83	35	11	0.93	4.5
5	45.473517	-73.886873	1048.83	35	11	0.93	4.5
6	45.543776	-73.839687	4471.36	35	10	0.93	8.5
7	45.558958	-73.90086	4233.07	35	10	0.93	8.5
8	45.526015	-73.929013	2172.61	35	10	0.93	8.5
9	45.513235	-73.956225	2172.61	35	10	0.93	8.5
10	45.499443	-73.968007	2172.32	35	10	0.93	8.5
11	45.512158	-73.964755	617.456	0	15	1	0
12	45.563189	-73.983275	3804.76	0	0	0	7.5
13	45.615289	-73.900191	3798.04	0	0	0	7.5
14	45.43119	-73.957087	1550.37	43	11	0.93	8
15	45.430829	-73.953139	1035.49	0	15	1	0
16	45.553076	-73.599566	5734.21	40	11	0.93	8
17	45.600549	-73.571945	5729.25	40	11	0.93	8
18	45.638371	-73.538642	4233.28	40	11	0.93	8
19	45.487212	-73.556747	1801.99	55	9	0.89	9.5
20	45.459964	-73.548806	1943.82	45	13	0.97	8

Table A1 – continued from previous page

Zone	Latitude deg	Longitude deg	Radius m	d_o m	h_o m	F	h_L m
21	45.470838	-73.541125	559.52	55	9	0.89	9.5
22	45.493436	-73.56647	2220.89	35	13	0.97	9
23	45.496555	-73.57172	1236.33	30	100	0.96	9
24	45.477628	-73.639895	6115.16	37	12	0.93	8.5
25	45.544292	-73.764239	4334.49	40	8	0.94	9
26	45.430243	-73.95103	1567.93	0	15	1	0
27	45.420916	-73.946202	538.3	0	0	0	7.5
28	45.442709	-73.603072	507.68	13	15	1	8
29	45.441032	-73.609005	257.27	13	15	1	8
30	45.443038	-73.596616	286.66	13	15	1	8
31	45.578561	-73.711505	3574.49	40	11	0.95	7.5
32	45.620783	-73.736125	1468.17	40	9	0.92	7.8
33	45.567735	-73.773246	469	50	8	0.6	11
34	45.573021	-73.775261	573.33	50	40	0.91	10
35	45.578094	-73.726646	3343.3	75	8.5	0.8	9
36	45.606471	-73.760197	981.7	0	15	1	0
37	45.608425	-73.721034	1745.27	40	9.5	0.92	7.8
38	45.573973	-73.732847	652.33	30	10	0.85	7.5
39	45.58667	-73.71821	475.18	30	10.5	0.85	8
40	45.581243	-73.712424	589.31	30	10.5	0.85	8
41	45.606794	-73.678565	2757.33	40	11	0.95	7.5
42	45.499381	-73.777284	1984.69	30	8	0.93	9
43	45.624484	-73.777209	1028.74	30	8	0.93	9
44	45.626746	-73.751446	1163.5	45	10	0.79	9
45	45.642074	-73.759972	1111.32	45	10	0.79	9
46	45.654009	-73.753926	565.21	45	10	0.79	9
47	45.628283	-73.646522	864.23	100	9	0.79	9
48	45.636819	-73.644179	704.06	100	9	0.79	9
49	45.669672	-73.580719	1135.41	35	10.5	0.9	9
50	45.655778	-73.594472	756.39	35	10.5	0.9	9
51	45.649959	-73.610008	748.64	35	10.5	0.9	9
52	45.685863	-73.593969	122.28	35	10	0.9	8
53	45.684019	-73.59329	158.31	35	10	0.9	8
54	45.687316	-73.624922	397.88	40	11	0.95	9
55	45.681938	-73.626754	378.97	40	11	0.95	9
56	45.685351	-73.640389	429.63	40	10.5	0.9	7.5
57	45.684927	-73.644576	513.06	40	10.5	0.9	7.5
58	45.578662	-73.810779	1885.89	40	9	0.92	7.5
59	45.669865	-73.581445	1176.66	40	6	0.87	7
60	45.658336	-73.595139	486.99	40	6	0.87	7
61	45.649695	-73.607701	943.64	40	6	0.87	7
62	45.619713	-73.736748	1577.7	40	9.5	0.92	7.8
63	45.605547	-73.802901	395.48	30	8	0.93	9
64	45.605643	-73.806192	170.05	93	6.5	0.86	20
65	45.603383	-73.805732	177.03	93	6.5	0.86	20
66	45.601263	-73.806303	138.59	93	6.5	0.86	20
67	45.596595	-73.80829	285.24	75	7	0.35	5
68	45.589523	-73.817458	598.77	40	8	0.98	7.5
69	45.579687	-73.785752	519.3	80	9	0.91	10
70	45.566742	-73.794239	956.48	95	9.5	0.86	9
71	45.564699	-73.783424	534.76	95	9.5	0.86	9
72	45.57769	-73.809499	1685.56	40	8	0.98	7.5

Table A1 – continued from previous page

Zone	Latitude deg	Longitude deg	Radius m	d_o m	h_o m	F	h_L m
73	45.57275	-73.779812	407.35	40	9	0.92	6.5
74	45.576025	-73.769727	434.77	40	9	0.92	6.5
75	45.577226	-73.76237	277.36	40	9	0.92	6.5
76	45.572138	-73.772153	177.08	40	9	0.92	6.5
77	45.534093	-73.788879	370.15	95	7.5	0.78	8
78	45.530072	-73.784738	373.43	95	7.5	0.78	8
79	45.526837	-73.780306	386.65	95	7.5	0.78	8
80	45.493572	-73.824689	2915.16	43	11	0.93	8
81	45.44632	-73.841687	5030.89	43	11	0.93	8
82	45.413312	-73.900346	1294.62	43	11	0.93	8
83	45.405117	-73.920945	1287.47	43	11	0.93	8
84	45.436933	-73.92663	485.53	43	11	0.93	8
85	45.414199	-73.958716	739.01	43	11	0.93	8
86	45.447606	-73.773278	1300.58	43	11	0.93	8
87	45.437128	-73.74873	1303.57	43	11	0.93	8
88	45.437151	-73.728026	1303.57	43	11	0.93	8
89	45.436428	-73.712233	1303.57	43	11	0.93	8
90	45.435847	-73.694037	1303.57	43	11	0.93	8
91	45.461948	-73.706166	1638.72	65	7	0.87	9.5
92	45.451977	-73.735921	1365.22	65	7	0.87	9.5
93	45.489822	-73.67055	938.96	65	6	0.85	9
94	45.489412	-73.685756	580.2	65	6	0.85	9
95	45.483317	-73.699904	1126.54	65	6	0.85	9
96	45.494602	-73.713477	1121.04	65	6	0.85	9
97	45.493228	-73.727198	1016.49	65	6	0.85	9
98	45.496296	-73.747347	1345.71	65	6	0.85	9
99	45.483364	-73.771305	1218.45	65	6	0.85	9
100	45.480148	-73.787168	719.05	65	6	0.85	9
101	45.477018	-73.797811	860.89	65	6	0.85	9
102	45.472685	-73.810858	737.6	65	6	0.85	9
103	45.467943	-73.820363	740.19	65	6	0.85	9
104	45.46204	-73.829461	633.07	65	6	0.85	9
105	45.455371	-73.841071	587.43	65	6	0.85	9
106	45.452773	-73.853174	434.61	65	6	0.85	9
107	45.450889	-73.859754	177.03	65	6	0.85	9
108	45.449305	-73.862786	177.03	65	6	0.85	9
109	45.447943	-73.866002	177.03	65	6	0.85	9
110	45.446649	-73.870508	274.22	65	6	0.85	9
111	45.444361	-73.875338	273.59	65	6	0.85	9
112	45.44284	-73.880347	230.01	65	6	0.85	9
113	45.440791	-73.889868	293.27	65	6	0.85	9
114	45.458772	-73.905955	488.75	43	11	0.93	8
115	45.402525	-73.946758	1367.94	43	11	0.93	8
116	45.427927	-73.905635	516.35	85	11	0.82	9
117	45.425306	-73.911214	441.22	85	11	0.82	9
118	45.421662	-73.918981	407.7	85	11	0.82	9
119	45.418576	-73.927174	442.58	85	11	0.82	9
120	45.422483	-73.928008	337.96	85	11	0.82	9
121	45.430551	-73.922325	339.98	85	11	0.82	9
122	45.439212	-73.67468	910.53	37	8	0.92	8
123	45.506652	-73.595021	946.73	15	15	1	8
124	45.501238	-73.603776	976.3	15	15	1	8

Table A1 – continued from previous page

Zone	Latitude deg	Longitude deg	Radius m	d_o m	h_o m	F	h_L m
125	45.479753	-73.555974	489.03	35	13	0.97	9
126	45.477135	-73.573088	1174.82	35	13	0.97	9
127	45.469233	-73.577894	1576.84	35	13	0.97	9
128	45.455685	-73.578583	1402.7	35	13	0.97	9
129	45.455324	-73.594204	1174.42	35	13	0.97	9
130	45.441617	-73.605908	1939.18	35	10	0.94	9
131	45.430776	-73.623245	2212.91	35	10	0.94	9
132	45.430535	-73.659809	1389.83	35	10	0.94	9
133	45.443726	-73.595941	241.4	2	15	1	0
134	45.442281	-73.603322	544.94	2	15	1	0
135	45.441619	-73.611304	119.46	2	15	1	0
136	45.440414	-73.613536	112.65	2	15	1	0
137	45.439993	-73.610961	112.65	2	15	1	0
138	45.511098	-73.687745	1808.9	40	11	0.93	8
139	45.516511	-73.724591	1734.61	40	11	0.93	8
140	45.531184	-73.6977	1821.15	40	11	0.93	8
141	45.537967	-73.680233	1243.1	40	11	0.93	8
142	45.540624	-73.652515	763.8	65	9	0.93	9
143	45.532847	-73.657335	756.39	65	9	0.93	9
144	45.534852	-73.628654	371.56	100	15	0.3	17
145	45.532056	-73.587713	178.69	10	15	1	17
146	45.526945	-73.568316	297.51	10	15	1	17
147	45.524484	-73.567667	193.12	10	15	1	17
148	45.525882	-73.570865	192.76	10	15	1	17
149	45.538685	-73.590452	142.93	100	15	0.3	40
150	45.539332	-73.5941	188.34	100	15	0.3	5
151	45.562269	-73.625156	519.59	0	0	0	7.5
152	45.564913	-73.633868	483.82	0	0	0	7.5
153	45.569832	-73.613291	144.84	0	0	0	0
154	45.572223	-73.615995	289.68	0	0	0	0
155	45.574607	-73.611108	296.16	0	0	0	0
156	45.576691	-73.623896	209.21	0	0	0	0
157	45.577986	-73.626797	209.21	0	0	0	0
158	45.579337	-73.630016	203.59	0	0	0	0
159	45.563097	-73.562043	603.88	50	15	0.5	0
160	45.569076	-73.556293	354.04	50	15	0.5	0
161	45.56661	-73.545697	628.63	150	9	0.85	10
162	45.564507	-73.531449	627.64	30	9	0.85	10
163	45.578913	-73.51808	1034.25	30	9	0.85	10
164	45.587119	-73.544519	266.44	100	15	0.2	0
165	45.588011	-73.548111	241.4	100	15	0.2	0
166	45.5889213	-73.552403	241.4	100	15	0.2	0
167	45.590504	-73.55618	237.65	100	15	0.2	0
168	45.589963	-73.561347	112.65	100	15	0.2	0
169	45.590414	-73.563085	109.74	100	15	0.2	0
170	45.591149	-73.565703	141.11	100	15	0.2	0
171	45.593125	-73.568101	153.25	100	15	0.2	0
172	45.617099	-73.604364	370.15	75	15	0.7	20
173	45.619891	-73.607488	374.1	75	15	0.7	20
174	45.622322	-73.61063	358.69	75	15	0.7	12
175	45.425901	-73.612466	261.16	75	15	0.7	12
176	45.601307	-73.610067	370.15	65	8	0.95	9

Table A1 – continued from previous page

Zone	Latitude deg	Longitude deg	Radius m	d_o m	h_o m	F	h_L m
177	45.606351	-73.604574	443.68	65	8	0.95	9
178	45.601908	-73.589897	403.82	65	8	0.95	9
179	45.599265	-73.583202	402.33	65	8	0.95	9
180	45.595563	-73.574813	402.33	65	8	0.95	9
181	45.599987	-73.564625	402.33	65	8	0.95	9
182	45.617505	-73.573595	1384.72	65	8	0.95	9
183	45.642984	-73.564979	520.76	65	8	0.95	9
184	45.647244	-73.557512	514.99	65	8	0.95	9
185	45.650664	-73.550713	514.99	65	8	0.95	9
186	45.653797	-73.544229	514.99	65	8	0.95	9
187	45.652699	-73.520683	847.72	65	8	0.95	9
188	45.645286	-73.515518	245.1	65	8	0.95	9
189	45.629559	-73.565273	553.62	0	15	1	0
190	45.627203	-73.560413	473.68	0	0	0	15
191	45.634786	-73.540334	2026.09	110	15	0.5	9
192	45.635317	-73.511496	397.62	110	15	0.5	9
193	45.653453	-73.580984	112.65	0	15	1	0
194	45.650783	-73.574353	112.65	0	15	1	0
195	45.649181	-73.572868	115.85	0	15	1	0
196	45.665821	-73.52684	767.75	0	0	0	7.5
197	45.669147	-73.493507	979.45	40	11	0.93	8
198	45.682365	-73.496987	981.7	40	11	0.93	8
199	45.695915	-73.48791	981.7	40	11	0.93	8
200	45.680895	-73.497232	340.81	0	15	1	0
201	45.670026	-73.514763	291.6	0	15	1	0
202	45.676246	-73.512102	418.06	0	15	1	0
203	45.680905	-73.512188	292.68	0	15	1	0
204	45.431493	-73.894652	572.65	0	15	1	0
205	45.439319	-73.913471	728.19	0	15	1	0
206	45.443898	-73.924428	415.84	0	15	1	0
207	45.450941	-73.928406	545.9	0	15	1	0
208	45.46597	-73.9361	1308.31	0	15	1	0
209	45.40949	-73.483236	2031.04	40	11	0.93	7.5
210	45.460311	-73.919206	462.48	43	11	0.9	8
211	45.384537	-73.567484	2654.36	40	11	0.93	7.5
212	45.38829	-73.517825	2391.21	40	11	0.93	7.5
213	45.365836	-73.510154	497.23	40	11	0.93	7.5
214	45.368097	-73.488407	612.36	40	11	0.93	7.5
215	45.375095	-73.490862	359.86	40	11	0.93	7.5
216	45.383713	-73.466433	528.53	40	11	0.93	7.5
217	45.390115	-73.486617	198.1	40	11	0.93	7.5
218	45.392521	-73.482472	269.4	40	11	0.93	7.5
219	45.401296	-73.594288	1028.76	45	7	0.7	13
220	45.39903	-73.512902	1029.98	60	7	0.85	13
221	45.398829	-73.498305	620.73	60	7	0.85	13
222	45.405579	-73.487061	627.64	0	0	0	7.5
223	45.44346	-73.466336	2336.13	40	11	0.93	7.5
224	45.491615	-73.455755	5334.41	40	11	0.93	7.5
225	45.504905	-73.380228	741.55	40	11	0.93	7.5
226	45.526102	-73.345277	2616.82	40	11	0.93	7.5
227	45.525959	-73.501946	2114.48	40	11	0.93	7.5
228	45.557552	-73.458245	3794.15	40	11	0.93	7.5

Table A1 – continued from previous page

Zone	Latitude deg	Longitude deg	Radius m	d_o m	h_o m	F	h_L m
229	45.592847	-73.430247	3707.6	40	11	0.93	7.5
230	45.589204	-73.345012	2024.99	40	11	0.93	7.5
231	45.62611	-73.448933	1376.51	40	11	0.93	7.5
232	45.661787	-73.430983	1059.7	40	11	0.93	7.5
233	45.682631	-73.42627	1757.84	40	11	0.93	7.5
234	45.572432	-73.464773	1573.29	60	9	0.96	9
235	45.567145	-73.442114	640.6	60	9	0.96	9
236	45.562097	-73.425977	1071.75	60	9	0.96	9
237	45.548221	-73.466156	532.35	0	15	1	0
238	45.55182	-73.471725	501.56	0	15	1	0
239	45.544908	-73.429411	1112.15	0	15	1	0
240	45.601691	-73.396831	1332.24	0	15	1	0
241	45.620184	-73.411938	1952.5	0	0	0	7.5
242	45.590527	-73.430877	241.4	65	11	0.9	8
243	45.593777	-73.434972	248.7	65	11	0.9	8
244	45.53419	-73.851753	537.21	80	15	1	0
245	45.531666	-73.848724	531.08	80	15	1	0
246	45.525668	-73.847035	236.5	80	15	1	0
247	45.530092	-73.87059	609.58	80	15	1	0
248	45.583708	-73.853991	819.97	35	11	0.93	8.5
249	45.639335	-73.844072	2524.36	35	10	0.93	9
250	45.612433	-73.840306	1346.83	35	11	0.93	7
251	45.620875	-73.867936	1181.61	35	10	0.93	4
252	45.63086	-73.819304	395.32	150	8	0.7	12
253	45.626125	-73.833429	294.62	65	8	0.91	10
254	45.622643	-73.828451	289.68	65	8	0.91	10
255	45.638235	-73.871145	823.41	90	8.5	0.92	9.5
256	45.635457	-73.860373	613.65	90	8.5	0.92	9.5
257	45.628755	-73.848429	611.55	185	8.5	0.7	13
258	45.644005	-73.839829	402.33	75	15	0.85	10
259	45.62046	-73.811862	1017.72	35	11	0.93	7.5
260	45.650328	-73.786076	1171.49	35	11	0.93	4.5
261	45.640103	-73.796167	1351.87	35	11	0.93	7.5
262	45.685073	-73.770836	3167.5	35	10	0.93	8
263	45.686239	-73.764711	781.05	80	8	0.91	9
264	45.693831	-73.754997	454.89	80	8	0.91	9
265	45.685292	-73.781511	450.62	65	8	0.91	9
266	45.732301	-73.651759	4943.41	35	10	0.93	8
267	45.717773	-73.617568	435.69	60	8	0.91	8
268	45.711828	-73.622	341.12	60	8	0.91	8
269	45.723656	-73.616404	485.45	130	8	0.75	13
270	45.728241	-73.67683	310.54	65	9	0.91	8.5
271	45.726383	-73.68301	252.41	65	9	0.91	8.5
272	45.724885	-73.689161	270.88	65	9	0.91	8.5
273	45.72099	-73.701264	500.39	100	9	0.88	8.5
274	45.718185	-73.709356	321.87	100	9	0.88	8.5
275	45.723627	-73.69517	318.72	65	9	0.91	8.5
276	45.715044	-73.715202	386.24	100	9	0.88	8.5
277	45.711868	-73.721554	386.24	100	9	0.88	8.5
278	45.706062	-73.719135	386.24	100	9	0.88	8.5
279	45.702607	-73.725064	391.93	100	9	0.88	8.5
280	45.694093	-73.601574	708.11	35	10	0.93	8

Table A1 – continued from previous page

Zone	Latitude deg	Longitude deg	Radius m	d_o m	h_o m	F	h_L m
281	45.701072	-73.58597	1021.75	35	10	0.93	8
282	45.704059	-73.552405	460.06	35	10	0.93	8
283	45.780634	-73.629427	715.04	40	7.5	0.94	7
284	45.717937	-73.512757	1813.91	250	7.5	0.7	15
285	45.715355	-73.499264	393.32	35	10	0.93	4.5
286	45.709849	-73.518397	708.11	35	9	0.93	7
287	45.721475	-73.517882	700.18	35	9	0.93	4.5
288	45.725952	-73.507309	491.42	150	25	0.7	12
289	45.358039	-73.736125	3138.21	35	8	0.93	7
290	45.347865	-73.686877	1096.88	70	9	0.91	9
291	45.366609	-73.710982	305.75	80	8	0.75	8.5
292	45.363505	-73.712964	110.71	80	8	0.75	8.5
293	45.361562	-73.713524	129.44	80	8	0.75	8.5
294	45.359212	-73.715659	158.96	80	8	0.75	8.5
295	45.358528	-73.719093	110.58	150	10	0.7	10
296	45.358851	-73.722002	122.72	150	10	0.7	10
297	45.359026	-73.72511	128.75	150	10	0.7	10
298	45.359377	-73.728149	111.96	150	10	0.7	10
299	45.359779	-73.731011	112.65	150	10	0.7	10
300	45.360172	-73.733924	112.65	150	10	0.7	10
301	45.356791	-73.7169	144.32	80	8	0.75	8.5
302	45.35474	-73.718359	111.27	80	8	0.75	8.5
303	45.35275	-73.719475	112.65	80	8	0.75	8.5
304	45.351001	-73.720419	112.65	80	8	0.75	8.5
305	45.342896	-73.765213	634.29	150	25	0.7	12
306	45.356592	-73.758567	144.84	40	12	0.93	5.5
307	45.357255	-73.755048	139.51	80	7	0.7	11.5
308	45.410403	-73.671463	956.46	35	7	0.93	7
309	45.411084	-73.689762	949.51	35	7	0.93	7

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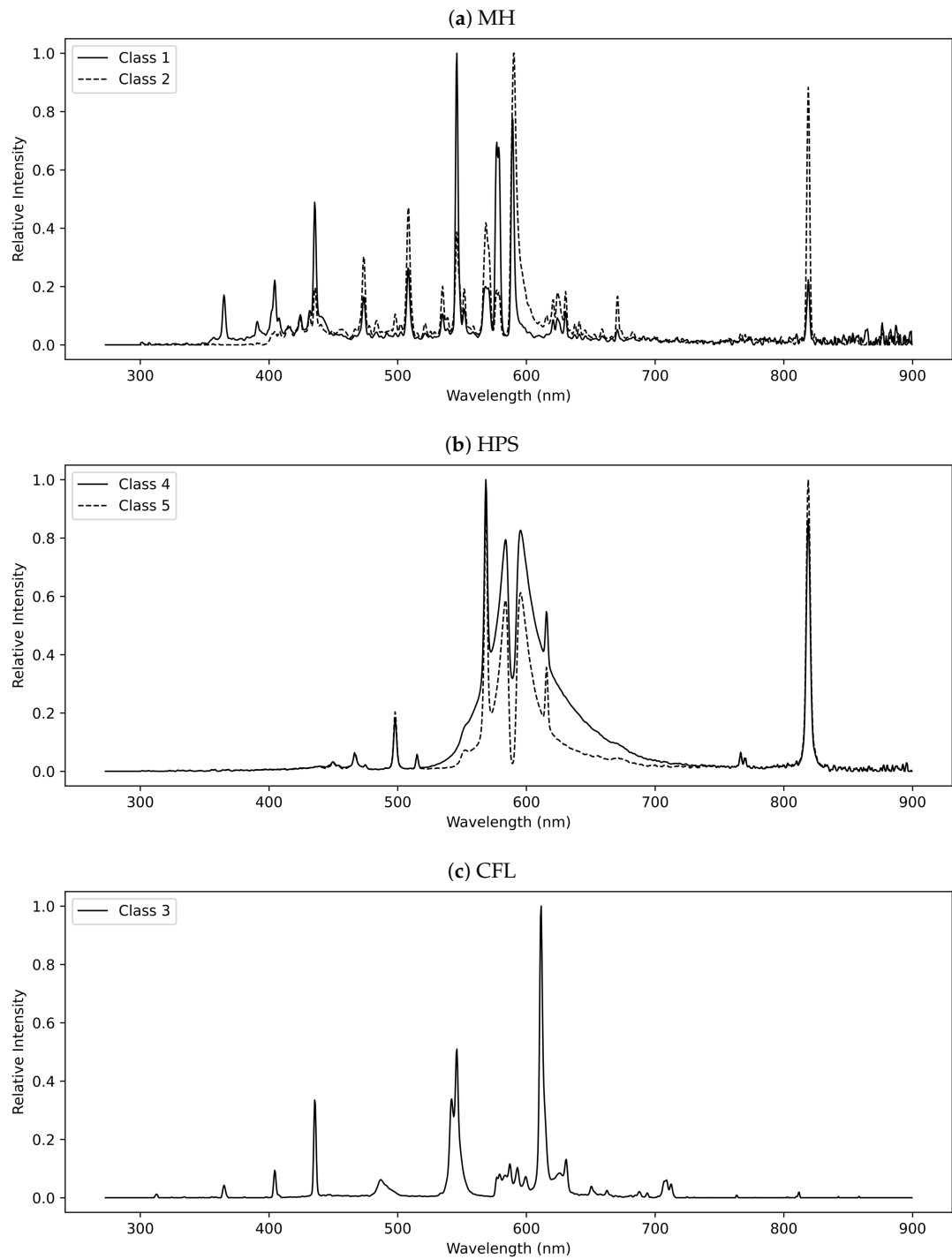


Figure 6. Spectra used for the modeling of Montréal in 2013.



Figure 7. The azimuth angle of a window facing the nearest street derived from the street network . This figure is for a small part of Montréal centred on site #2 of Table 3. The white star marker indicates the position of site #2.

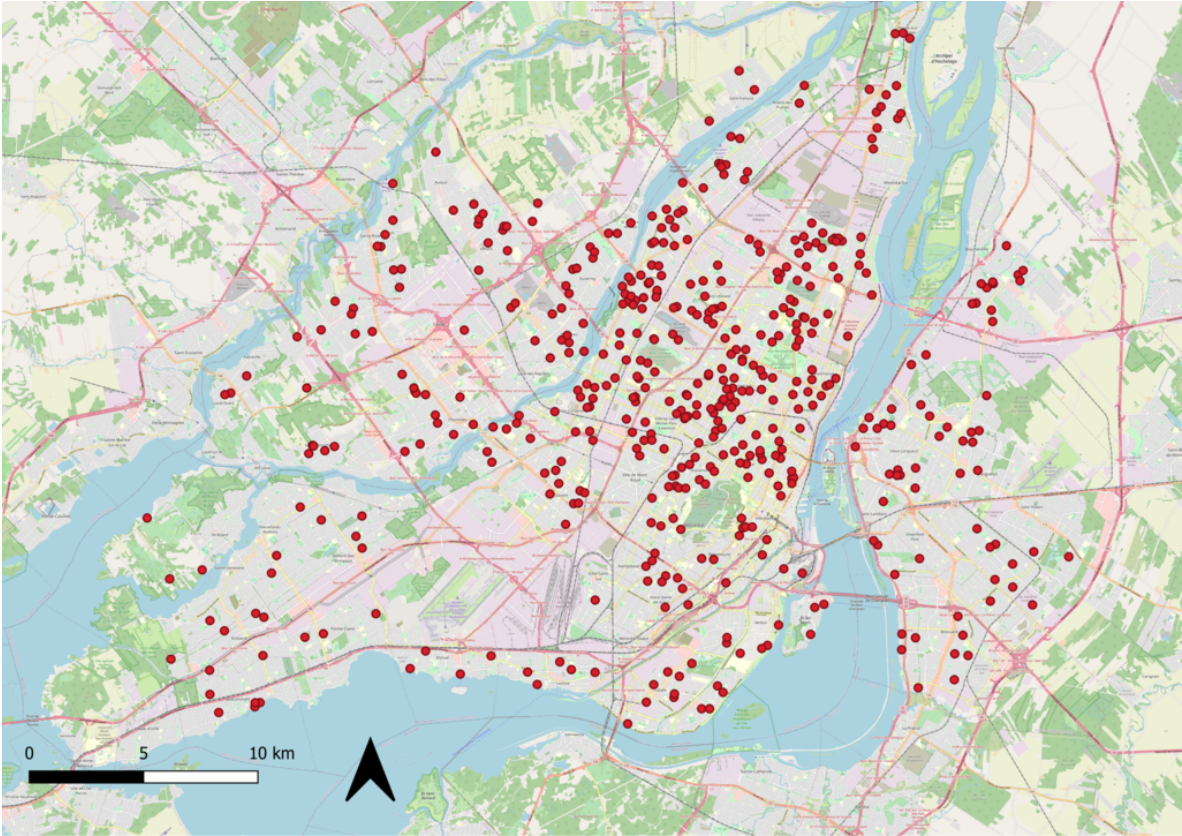


Figure 8. The location of the 500 sampling points across the city of Montréal.

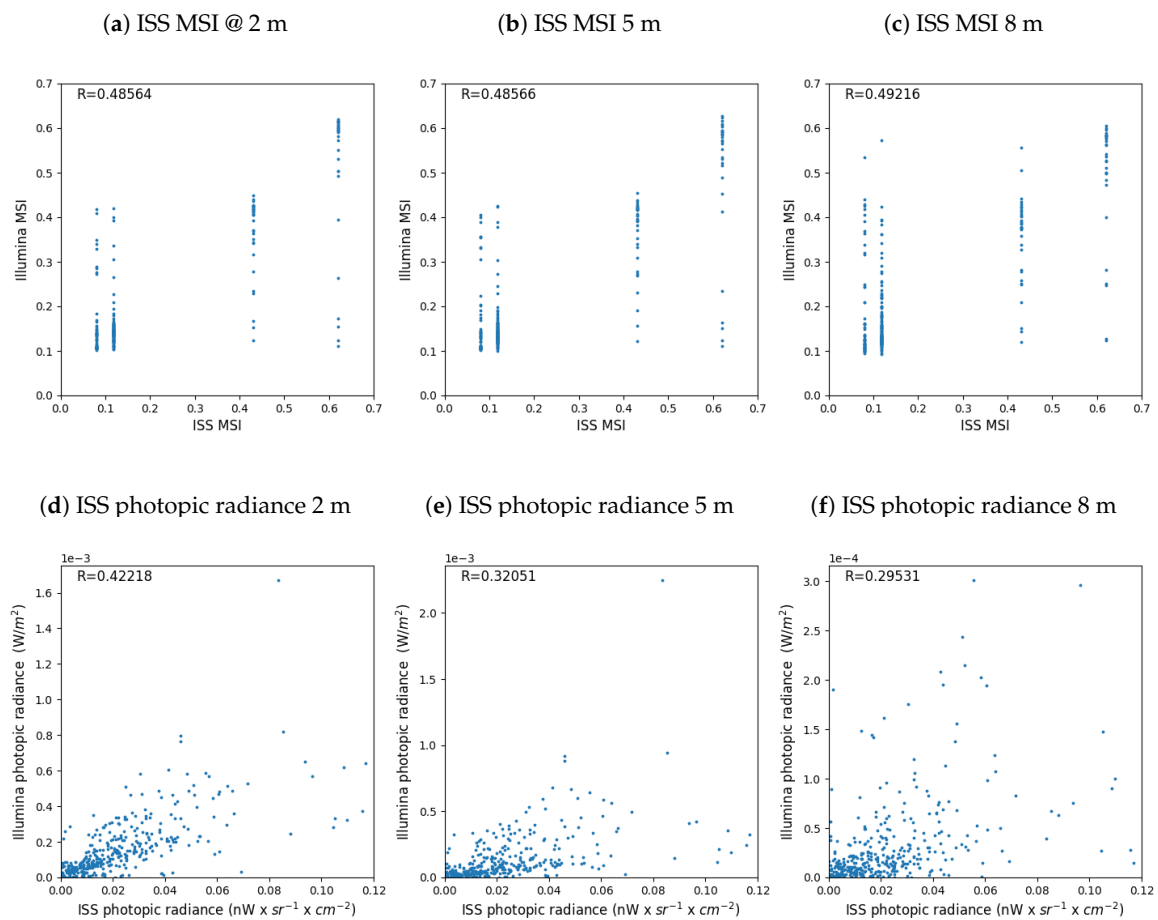


Figure 9. Scatter plots between the remotely sensed ISS MSI and MSI derived with Illumina v2 in panels (a),(b) and (c) respectively for window heights of 2, 5 and 8 m. Panels (d), (e), and (f) show the scatter plots between the remotely sensed upward ISS photopic radiance and the Illumina photopic irradiance for the same set of window heights.

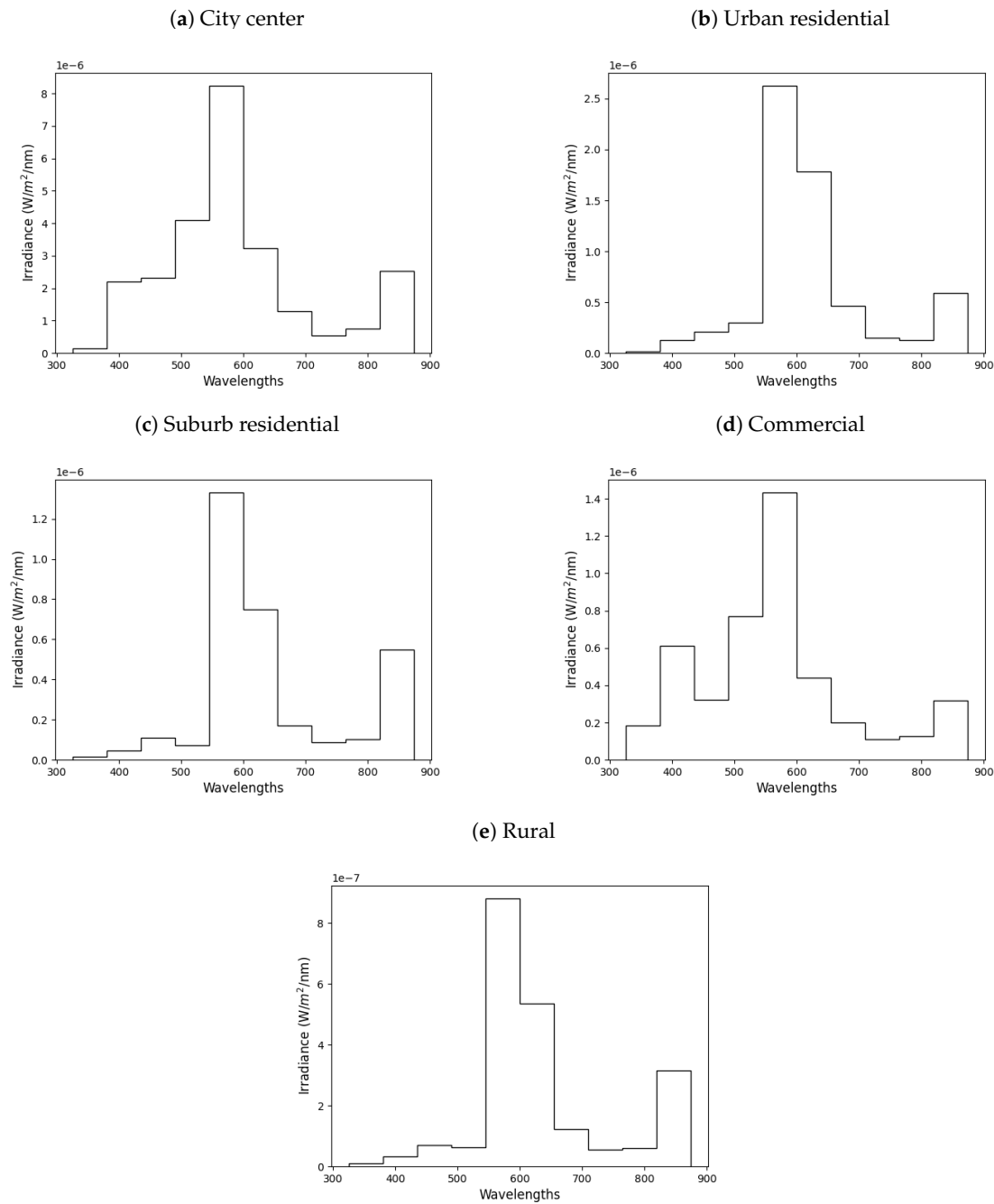


Figure 10. Spectral irradiance on windows 2m above ground for the five test sites identified in Table 3.