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Characterizing urban heat island in Montreal (Canada)—Effect of urban morphology

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ABSTRACT

The urban and built-up class is the most complex land category interacting with the atmosphere. In assessment of urban heat island intensity (UHII), urban canopy models (UCM) are coupled to mesoscale models to account for the momentum, heat, and turbulence kinetic energy of buildings. Since considering the actual structure of an urban area is not feasible, ideal urban geometries are proposed. Moreover, realistic estimation of mean height of buildings, deviation of building heights, frontal area density, and plan area density of a city is required for urban climate modeling. In this paper, we have selected four neighborhoods in Montreal (Canada) to compare UHII using a typical urban structure that has been proposed by earlier studies with UHII using the urban morphology of Montreal in current research. Simulations with Weather Research and Forecasting model coupled to a multi-layer urban canopy model and building energy model suggest that the UHII of Montreal can be underestimated by up to 1.2 °C (at 9 am) in July 14th, 2005, when urban morphology is not accurate. The energy consumption of buildings is also underestimated by a factor of three.

The UCM has a detailed procedure that considers the multi-reflection between urban surfaces to estimate the energy budget of the canopy. Major portion of the absorbed energy in the canopy is from the solar radiation on urban surfaces, which is highly dependent on their sky view factors. We propose a new parameterization for sky view factor of walls and compare it with other parameterizations and approximated field data. Implementing the new parameterization decreases the predicted UHII and the energy consumption by 0.4 °C and 1% in the simulation period, respectively.

1. Introduction

Urban areas are complex surfaces that current urban canopy models (UCMs) are not able to consider in all their details. Therefore, in numerical weather prediction, a practical method of assuming uniform distribution of buildings in the urban grids is applied (Martilli, 2009, and references therein). Higher solar irradiance during the day is the dominant factor affecting the energy balance on the ground (Taha, 1997). Urban areas with lower albedo absorbs more than 80% of the solar energy that increases their air temperature compared to rural areas, called urban heat island (UHI). To fight undesirable consequences of UHI, scientists have proposed different mitigation strategies; such as, (1) increasing the urban albedo, (2) increasing the urban vegetation, and (3) decreasing the anthropogenic heat emission. Mesoscale models use UCMs, for better prediction of vertical heat and moisture fluxes, in evaluation of mitigation strategies. An accurate estimation of the geometry of urban canopy can improve the fluxes from urban areas to the atmosphere. Among different influential parameters, leveraging the correct sky view factor (SVF) is a crucial part of energy calculation in UCMs (Park & Tuller, 2014). Too many efforts have been made to characterize the effect of SVF on outdoor thermal environment (He et al., 2015) and built environment (An et al., 2014; Chen et al., 2012; Groleau & Mestayer, 2012). Additionally, various methods have been proposed to determine the SVF (Kastendeuch, 2013; Debbage, 2013).

In general, UCMs are divided into 1D (buildings and streets are considered as a roughness of the surface; this option is not accurate for modeling urban heat island, Touchaei & Akbari, 2013), 2D (buildings are distributed alongside streets), and 3D (two different orientations are considered for streets, which divides buildings into blocks). 2D UCMs assume rows of buildings with equal width, and constant or randomly distributed height. Whereas, for the sake of simplicity, 3D models only consider buildings with constant height and width. The effect of assuming 2D and 3D streets on the SVF in

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urban canopy models was tested for five cities in Europe and Northern America (Martilli, 2009). Analytical approaches in calculating SVF are sophisticated and need simplification of urban geometry (Johnson & Watson, 1984). One of the well-accepted methods to determine the SVF is image processing of fish-eye photography (Steyn, 1980;, Hämmerle, Gál, Unger, & Matzarakis, 2011) or aerial images (Brown, Grimmond, & Ratti, 2001; Ratti, Di Sabatino, & Britter, 2005). However, the empirical method is costly. The last option to calculate the SVF is to use numerical methods that are cost-efficient and accurate in the scale of urban areas (Unger, 2009; Kastendeuch, 2013).

Urban geometry is described by three main factors; mean building height (h_m), plan area density $\left(\lambda_p\right)$, and frontal area density $\left(\lambda_f\right)$. Considering a 2D street where the building size (b) and street width (w) are known, plan area density and frontal area density are as follows:

$$\lambda_p = \frac{b}{b+w} \tag{1a}$$

$$\lambda_f = \frac{h_m}{b+w} \tag{1b}$$

Similarly, for a 3D street with identical buildings following equations should be used.

$$\lambda_p = \frac{b^2}{(b+w)^2} \tag{2a}$$

$$\lambda_f = \frac{bh_m}{(b+w)^2} \tag{2b}$$

The mean building height, plan area density, and frontal area density for selected cities were empirically estimated by Ratti et al. (2002). The sky view factor for 2D and 3D streets was calculated based on proposed models of Martilli, Clappier, and Rotach (2002) and Kanda, Kawai, and Nakagawa (2005), respectively. Based on results, the 2D street model estimates the sky view factor of the canopy better than the one using 3D streets. The error of the 3D street model is an order of magnitude larger than that of the 2D street model.

In this paper, first, we analyze the urban data of four different neighborhoods in Montreal (Canada). Then, we simulate the UHI in Montreal using the typical urban characteristics (Chen et al., 2011). We evaluate four methods to represent urban morphology and compare street SVF values for the case studies in Martilli (2009) and for Montreal. Like Martilli (2009), we are not addressing the effect of urban morphology on wind pattern inside the canopy because computational fluid dynamics is the accepted method of evaluating the microclimatic effect of canyon geometry on urban climate, which is not in conformity with our objectives and methodology. Three sets of simulations are performed to investigate the effect of (1) modified urban geometry, (2) modified SVF (using statistical modeling for parameterization), and (3) modified urban geometry and modified SVF on urban heat island intensity (UHII). The objectives are twofold: (1) to quantify the difference in UHII of Montreal between typical and accurate urban morphologies on a summer day, (2) to modify the SVF of road and to test the modified SVF by calculating UHII.

2. Methodology

Step 1. Aerial images of selected neighborhoods are collected and building heights are extracted from the database of Montreal Municipality (City of Montreal, 2009). From the data, mean building height and deviation of buildings heights are calculated. Line drawings of the neighborhoods are provided to identify actual plan area density and frontal area density. The plan area density is the fraction of number of pixels with buildings to total number of pixels from top view. The frontal area density is mean of fractions of pixels with buildings from four side views (north, east, west, and south) to total number of pixels from the top view. The average of calculated parameters is considered as the characteristic of the city.

Step 2. The building energy model (BEM) calculates energy consumption and heat emission of buildings. The BEM (Salamanca & Martilli, 2010a) calculates the energy demand of the building that keeps the indoor air temperature and the indoor moisture content in the comfort range. The accuracy of BEM is restricted by the dynamics of HVAC systems and by characteristics of building envelopes. HVAC systems of buildings are diverse and their efficiency/performance is highly dependent on the exerted load (part-load ratio). Building envelopes are also different in terms of materials properties such as reflectance, insulation, and emittance. In an idealized urban structure all buildings and their HVAC systems have the same characteristics. A simple method is used to find the average efficiency of heating systems and COP of cooling systems. The share of each energy system in total energy consumption for cooling or heating in Quebec is calculated from the data provided by the Energy Use Data Handbook (Behidj et al., 2012; Office of Energy Efficiency, 2011; and references therein). Then, the weighted average of performance of the energy systems is calculated to represent efficiency of heating systems and COP of cooling systems.

Step 3. The air temperature of Montreal is simulated using version 3.5 of the weather research and forecasting model (WRF). The platform for mesoscale modeling is the same as our previous research (Touchaei & Akbari, 2014; Appendix A). The fine-resolution grids (500 m × 500 m) provide more detailed information on different neighborhoods in Montreal at the cost of poor accuracy because of the deficiency of microphysics parameterizations. For modified morphological parameters only URBPARM.TBL is updated and for the modified sky view factor the source code for UCM is altered.

Step 4. A SVF parameterization is proposed by statistical analysis of hypothetical urban configurations. A set of urban geometry with randomly distributed building heights is developed to find the relation between the actual SVF and the estimated SVF using different techniques. A simple UCM code is developed with MATLAB 2012R to numerically calculate view factors of different surfaces and the total absorbed energy by the canopy using numerical methods.

The sky view factor (SVF) of streets in idealized urban structures (London, Toulouse, Berlin, Salt Lake City, Los Angeles, and neighborhoods in Montreal) is determined and a new parameterization for SVF is calculated. The actual SVF (F_{rs}) is compared with calculated SVFs (F_i) to investigate the accuracy of different methods. Actual SVFs of five cities are collected from the previous study (Martilli, 2009). ENVI-met software (Bruse and Fleer, 1998) is used to calculate SVF of the neighborhoods in Montreal and the average is used for the city. Nine receptors are placed in each neighborhood, in the middle of streets, to calculate the SVF. The ENVI-met model is capable of separating the SVF calculation accounting for the effect of buildings and vegetation. The F_{rs} is calculated by averaging the SVFs observed in 9 receptors.

Step 5. The urban heat island intensity in simulations is calculated by subtracting the spatially averaged 2-m air temperature of rural areas from the spatially averaged 2-m air temperature of the urban area, on an hourly basis. In the simulation domain (~50 km × 30 km), the total number of grids is 3 times more than the number of grids considered as urban. The actual UHII is identified by subtracting the measured temperature in a weather station located in the rural area (Mirabel Airport weather station) from the measured temperature inside the urban area (McTavish weather station).