3D Simulation Analysis of Urban Micro-Climates to Inform Heat Island Mitigation Policies in Cold Climates

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ABSTRACT

Currently, in Canada, some municipalities have discussed UHI mitigation at strategy level, carried out literature review, revealed current status of UHI impacts in Canadian cities on energy consumption, citizen wellbeing and health. However, there is little discussion about detailed technical guidelines for UHI mitigation application. Changes in temperature and air quality within cities resulting from climate change will lead to greater discomfort of urban residents both indoors and outdoors, negative health impacts and fatalities amongst urban dwellers. Meanwhile, urban climate change in cold climate cities of Canada is an important consideration in global climate moderation, energy consumption reduction, citizen safety and wellbeing. Many Canadian municipalities are planning and implementing climate change adaptation and mitigation strategies. They need policy-relevant data and analysis to support evidenced based policy making and monitoring initiatives. Although many municipalities have community greenhouse gas (GHG) emissions inventories, bottom-up scenarios for mitigating energy use and urban heat island (UHI) effects are far less common.

In this research, we discussed about the policy implement; demonstrated how the building surface materials affect urban climate and urban air quality in two Canadian cities, Montreal, Quebec and Toronto, Ontario. Comparison of varied urban surface materials was carried out. The effect of cool roof and cool wall on UHI mitigation is demonstrated by numerical simulation in these two cities provided policy-relevant data analysis, which are not included in current policies. We discussed about UHI mitigation policies in this cold climate city. This research supports sustainable urban development and in cold climate Canadian cities.

Introduction

The urban heat island (UHI) effect describes the phenomenon when an urban agglomeration is warmer than its rural surroundings. It occurs because building and street surface materials have high heat capacities; these materials capture heat during the day and release it slowly at night. The adverse energy and environmental implications of UHIs and mitigation methods have become major research topics in sustainability programs. For example, reducing energy use in buildings is an important topic in environmental engineering.

Daytime solar energy absorption is the primary cause of the urban heat island effect in summer. Pavements and roofs comprise over 60 percent of urban surfaces. Dark materials, dark pavements and roofs, absorb between 80 and 90 percent of sunlight. Lighter materials, white roofs and lighter colored pavements, absorb only 30 to 65 percent of sunlight. There is an interaction of thermal radiation between roof, wall and ground surfaces. The use of reflective building surface materials is a key solution for UHI mitigation [*Akbari et al. 1997; Berdahl and Bretz 1994; Bretz et al. 1997; Bretz and Akbari 1997; Konopacki and Akbari 2001; Synnefa et al. 2007; Synnefa et al. 2006; Taha et al. 1988*].

A number of studies are currently attempting to characterize the UHI effect in cities. Some are using averaged Land Surface Temperature (LST) [*Jin 2012; Gupta 2012; Peng et al. 2012*] derived from satellite data. However, observed LST depends on spatial resolution, because of the different land cover types. In most present studies, a spatial resolution of 1 km^2 is used. This ignores land cover characteristics on a community scale. Furthermore, LST derived from the satellite database ignores the contribution from the surface of exterior building walls. This is a serious deficiency for the consideration of urban solar heat absorption and reflection. This is especially relevant for large cities with high density of high-rise buildings. This research will run simulations and evaluate the urban community thermal environment for assessing the impact of building surface solar reflectance on the UHI effect.

Many researchers have focused on the building surface materials, LST and urban heat island problem. Most studies have analyzed measured climatological data and demonstrated the correlations with urban development [*Rao 2012; Jin 2012; Rupesh 2012*]. The effect from local microclimate on the demands for energy in buildings is discussed through simulation [*Robinson 2004; 2007*]. The calculation for solar irradiation absorption has been developed in simulation programs [*Robinson and Stone 2004; Bruse 1999*], and the contributions to UHI from urban surfaces are also investigated [*Robinson et al. 2007; Page et al. 2008*]. In this research, thermal radiation from urban surfaces such as building roofs, and exterior walls will be simulated using a micro-scale urban simulation model. In this research, both an urban and a community scale will be analyzed. The simulation will be helpful to determine the contributions of each component, and to determine the optimal combination of urban surface properties.

Significance Of UHI Impact In Cold Climates

The UHI effect is studied in several hot and dry cities, whereas discussion about UHIs in cold climates is rare. Nonetheless, understanding UHIs in cold cities is an important to inform climate change mitigation and energy use reduction strategies. For example, research carried out in eight Canadian cities compared observed number of annual hot days (with a temperature high of 30 ℃) between 1961 and 1990 to the forecasted average after 2020 will be increased from 10 to 22 days. Projected temperature increases in Canada are even more dramatic than in the southern latitudes [*Heath Canada, 2011*].

Health Canada reported that in 7 Canadian cities, when the daily average temperature is higher than 20 ℃, the relative mortality is increased by 2.3% for every degree increase in the air temperature; a UHI intensity of 2-3 ℃ translates into a 4 to 7 percent increase in the mortality rate. Over seventy percent of Canadians are living in urban areas. UHI, global warming and their effects on electricity infrastructure is a significant threat to Canadian safety and security, community safety and citizen wellbeing.

The combination of UHI and global warming effect will lead to a higher demand for air-conditioning contributing to electricity system peaking putting pressure on electricity generation, transmission and distribution infrastructure. The possibility of blackouts during extreme temperature events is a significant public health threat. Heat waves significantly impact the amount of electricity use. Hotter summer temperature increases the demand for electricity, and the trend is evident in Ontario. Electrical demand during the peak hours in summer has risen steadily from 1994 through 2002 [*Liu 2003*]. The gross energy consumption in a high rise building is much higher than that in low rise building. The risen electricity demand and high building density have caused damage in Toronto. In August 2003, hot weather and high electricity demand caused transboundary blackout shut down Toronto's operations for nearly 3 days [*US-Canada Power system Outage Task Force 2004*]. On the other hand, from 1993 to 2005, the proportion of Quebec households with a home air conditioner is increased from 15.2% to 36.4% [*Institut de la statistique du Quebec 2005*]. This is potentially contributes to electricity demand rise in a hot summer day, becoming to be a hidden danger in Montreal.

UHI mitigation is discussed at strategy level in Toronto and Montreal, and the city of Toronto has developed a made-in-Toronto Green Development Standard (GDS) to provide guidance to build green in communities [*Wieditz and Penney, 2007; Giguere, 2009*]. Building energy consumption mitigation guidelines are carried out, in order to reduce GHG emission [*CAP 2013*]. However, the detailed technique implement about building envelop performance and local urban comfort is not demonstrated. This study extends the consideration of UHI mitigation to cold cities of Canada, demonstrate and explicate the effect with numerical simulation. This research will be an investigation of the methodology for UHI study, which could provide hints to provincial governments for establishing the environmental urban planning standards, what can be used in urban developments and redevelopments.

Methodology

Policy Analysis

Policy document analysis was carried out for Toronto and Montreal city to grasp the current status and context of UHI mitigation policy development. These documents include official government documents and council reports. Through reviewing the current policies, focused on the elements that need to be improved, provided support data for these standard development. This analysis will help to describe what efforts have been carried out by the governments and councils, and figure out the insufficient component of this policy system.

Urban Environmental Simulation

We used ENVI-met simulation model (a three-dimensional computer model that analyzes micro-scale thermal interactions within urban environments) to simulate the environmental conditions in the selected area. ENVI-met is designed to simulate the surface-plant-air interactions in urban environments. It has a typical spatial resolution of 0.5m to 10m, and a temporal resolution of 10 seconds. A simulation is typically carried out for at least 6 hours, usually for 24-48 hours. The optimal time to start a simulation is at night or sunrise, so that the simulation can follow the atmospheric processes. ENVI-met requires an area input file which defines the 3-dimensional geometry of the target area. This includes buildings, vegetation, soils and receptors. A configuration file, which defines the initialization input, is also required [*Bruse 2013; 1999; Ozkeresteci et al. 2003*].

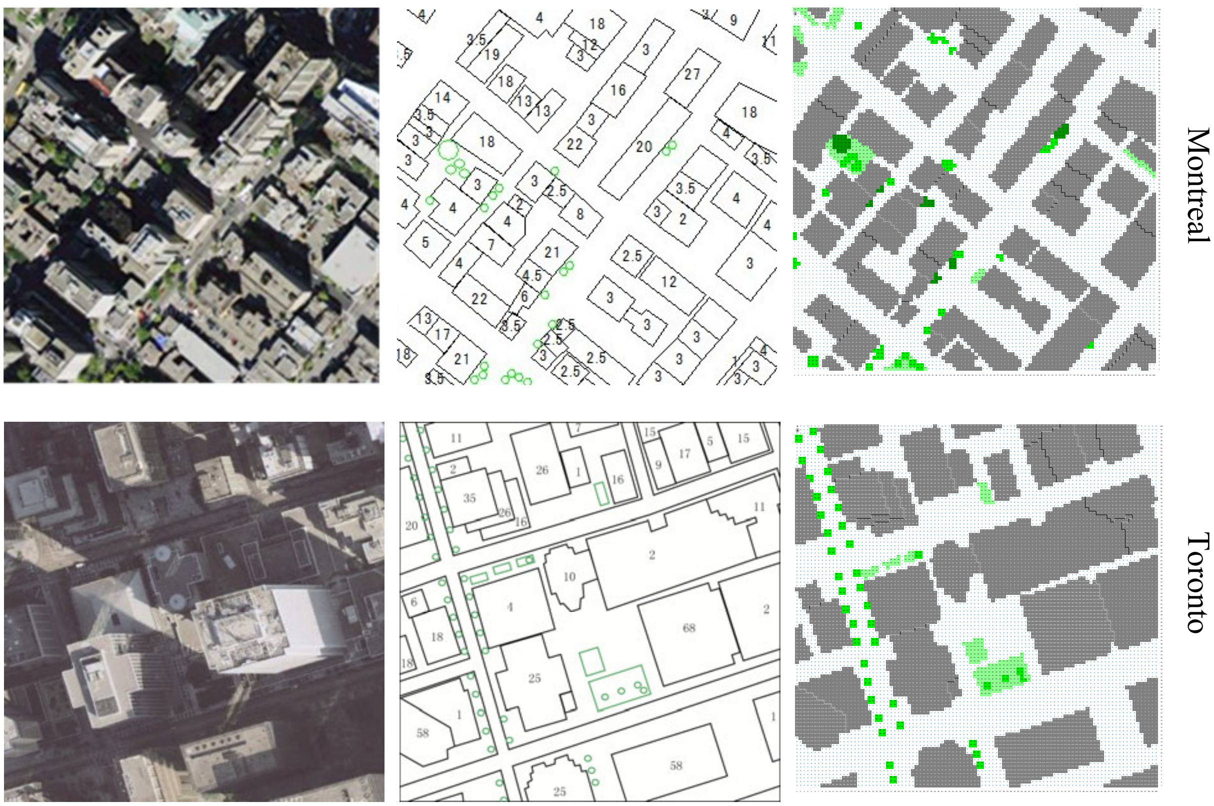
LiDAR (Light Detection and Ranging) is a remote sensing technology that measures distance by illuminating a target with a laser and analyzing the reflected light [*NOAA 2013*]. It is more accurate from a building geometry, urban tree canopy/shading perspectives than sketch-up models. However, the output data from LiDAR can't be directly input into ENVI-met system. Currently, the only way to build up an ENVI-met model is to define the height of buildings and landscape condition grid by grid. For these simulations, the geometry of urban street canyons in selected area is identified using satellite pictures and street view 3D maps from Google Map.

Area input files were built by ENVI-met; we input satellite pictures into the editing files, and defined the ground, vegetation, building facade and building layout by cubic grids of 27m^3 (3m×3m×3m). The simulations were run for 24 hours, starting from one hour before sunrise (4am). We simulated this area in summer. The weather data was obtained from the "Weather Spark" database. However, with the spatial limitation of the simulation model, a deviation will emerge around the edge of simulation model. This deviation will also affect the UHI simulation results with ENVI-met.

Simulation Areas

In Montreal a high-density residential area next to the city's main commercial area and a university was selected. It contains 74 buildings, of which 13 are high-rise residential buildings of more than 15 floors. Within the 90000 m^2 area, 45360 m^2 is roadway asphalt.

The area in Toronto is the central business district with high-rise office buildings. The highest one reaches up to 68 floors. It contains 28 buildings, of which 14 are high-rise residential buildings of more than 15 floors.



Aerial satellite view | CAD map | Area input file to the ENVI-met

Figure 1. Images of the selected areas: 1) aerial satellite view pictures, 2) CAD map include floor numbers for simulation inputting, and 3) input file images for ENVI-met simulations, based on the aerial satellite view pictures.

Policy Implication

Recently, many Canadian cities such as Toronto, Montreal, and Vancouver have started to pay attention on climate change adaptation and mitigation strategies [*City of Vancouver, 2007;*

Wieditz and Penney, 2007; Giguere, 2009]. The discussion about UHI mitigation is still at strategy level in Toronto and Montreal, although the city of Toronto has developed standards to induce vegetation planting in the city. Building energy consumption mitigation guidelines are also carried out, in order to reduce GHG emission [*CAP 2013*]. However, there are resistances of acting on climate change at local level, such like socio-cultural and institutional barriers [*Burch 2010; Burch 2010*]. They need policy-relevant data and analysis in these efforts, to establish detailed technical standards and guidelines at local level. The current data mostly focus on the consideration of greenhouse gas emission level, rather than providing identified mitigation scenarios at urban scale [*Johnson et al. 2013*]. In developing UHI policies to address climate change, due attention should be given to the comprehensive urban development process [*Sheppard et al. 2011*]. Such detailed guide lines for urban climate change mitigation is already carried out for cities in Japan and the United State [*Akbari et al. 1992; Takebayashi and Moriyama 2009*]. The innovative investigation and development of a thorough guideline which adapt to the cold climate and social culture in Canada is becoming an essential demand. Beside the scientific demonstration, the socio-political and economic issues are also playing a significant role in the implementation process [*Aylett 2010*]. Moreover, socio-political inequalities often exclude and disempower specific actors, and properly designed institutions could ensure the participation [*Wu et al. 2013*]. Policy analysis for adaption to the local culture and local institutional development should be discussed.

Urban Typology

Outgoing long-wave radiation at night is one of the most effective cooling methods of UHI. 3D geometrical configuration plays an important role in managing long-wave radiation heat loss. Outgoing long-wave radiation depends on the urban design, due to the fact that only a small part of the sky is seen from the ground surface caused by narrow streets and tall buildings creating deep canyons. The sky view factor (SVF) can be a representative indicator for urban building density and layout. SVF is the ratio of the radiation received (or emitted) by a planar surface to the radiation emitted (or received) by the entire hemispheric environment [*Rosenfeld et al. 1995*]. Videlicet, SVF impacts urban radiation exchange and urban microclimate. While, numerous studies have studied the effect of SVF on UHI [*Gal et al. 2009; Unger 2004*], few have actually performed quantified analysis relating the outdoor thermal comfort to urban heat island. Most studies have focused on UHI intensity (the comparison between urban and rural areas) but not radiation transfer between various urban surface geometries inside urban areas.

SVF is an index to express the landscape openness, which changes with building height, building volume, and building separation. SVF control could be achieved by several building development index control such as floor area ratio, building set back, building coverage ratio, that all are related to urban density control. Urban density control in residential area is carried out and discussed widely for reasonable urban function planning and economic development, and the transportation cost [*Mills, 2005*]. SVF control is an additional consideration about sustainable urban development in long term. Further analysis on the relationship between urban SVF control and urban density control should be carried out in future research.

Building Surface Materials

A dark roof is heated by the sun and directly raises the summertime cooling demand of the building beneath it. For this reason, "cool" roofs can be effective in reducing cooling-energy use. Several field studies have measured energy savings that result from increasing roof solar reflectance [*Akbari et al. 1997; Akbari et al. 2001*]. Computer simulations of cooling energy savings from increased roof reflectance have been documented in residential and commercial buildings [*Bretz and Akbari 1997; Takebayashi and Moriyama 2007*]. The urban cooling effect and reduced cooling energy use and air quality improvement are documented in [*Yarbrough and Anderson 1993*]. Other benefits of cool roofs are longer life and reduced material waste [*Synnefa et al. 2006*]. Possible problems with using reflective roofing materials are studied in [*Berdahl and Bretz 1997; Levinson et al. 2005*]. Most reflective roofing materials are light colored, although selective surfaces that reflect a large portion of the infrared solar radiation but absorb some visible light can be dark colored and yet have relatively high solar reflectance [*Synnefa et al. 2007*].

Paving Materials

An overview of cool paving materials is presented in [*Lowry 1977*]. Cool pavements result in lowered ambient temperatures. Lower temperature has two effects: 1) reduced demand for electricity for air conditioning and 2) decreased production of smog (ozone). Rosenfeld et al. estimated the cost savings of reduced demand for electricity and of the externalities of lower ozone concentrations in the Los Angeles Basin [*Akbari et al. 1997*]. Also, it has long been known that the temperature of a pavement affects its performance [*Bahadur 2009*]. Reflectivity of pavements is also a safety factor in visibility at night and in wet weather, affecting the demand for electric street lighting. For pavements, the initial higher cost may be offset by lifetime savings through the energy and smog savings and substantially longer lifetime of cool pavements.

Urban Vegetation

Overviews of benefits and cost associated with planting urban trees are summarized in [*Oke 1988*]. Researchers have measured and simulated the wind-shielding effects of tree on heating- and cooling-energy use [*Blankenstein and Kuttler 2004*]. Trees also decrease the wind speed under their canopy and shield buildings from cold winter breezes. The wind-shielding impact of trees on heating-energy use in four Canadian cities is studied. Taha et al. simulated the meteorological impact of large-scale tree-planting programs in 10 U.S. metropolitan areas. Rosenfeld et al. [*Rosenfeld et al. 1995*] studied the potential benefits of planting 11M trees in the Los Angeles Basin. Trees also offer benefits including CO_2 sequestration, improvement in the quality of life, increased value of properties, decreased rain run-off water and hence a protection against floods. There are some potential problems associated with trees such as volatile organic compounds (VOCs) emissions, irrigation needs, and maintenance. Low-cost tree planting programs can be designed so they can offer savings to communities that plant trees.

Results

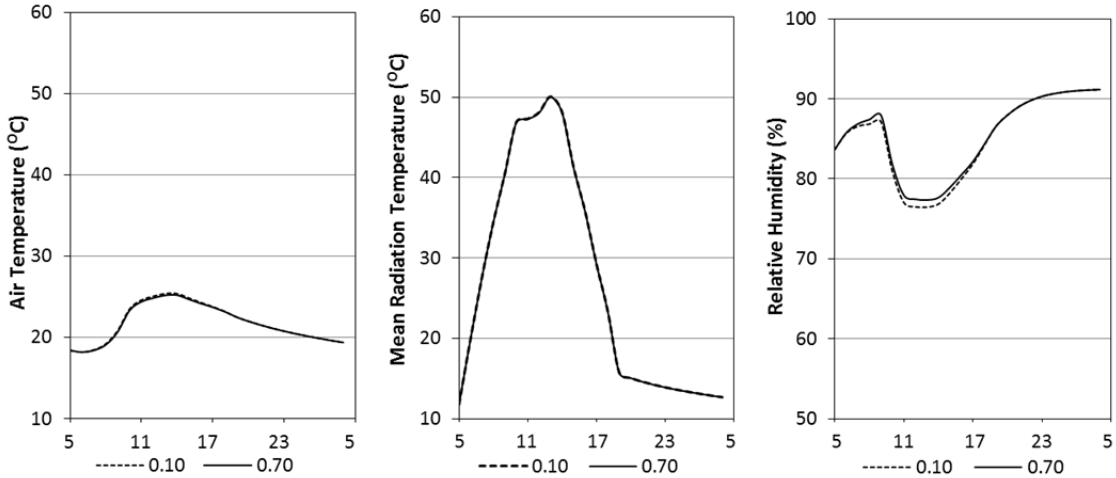


Figure 2. Averaged diurnal air temperature (Ta), mean radiation temperature (Tmrt), and relative humidity at 1.8m above the ground on a typical Summer day (from 5am, 22 July, to 4am the next day) in the selected area of Montreal, with two roof types (Type 1: albedo 0.10; Type 2: 0.70).

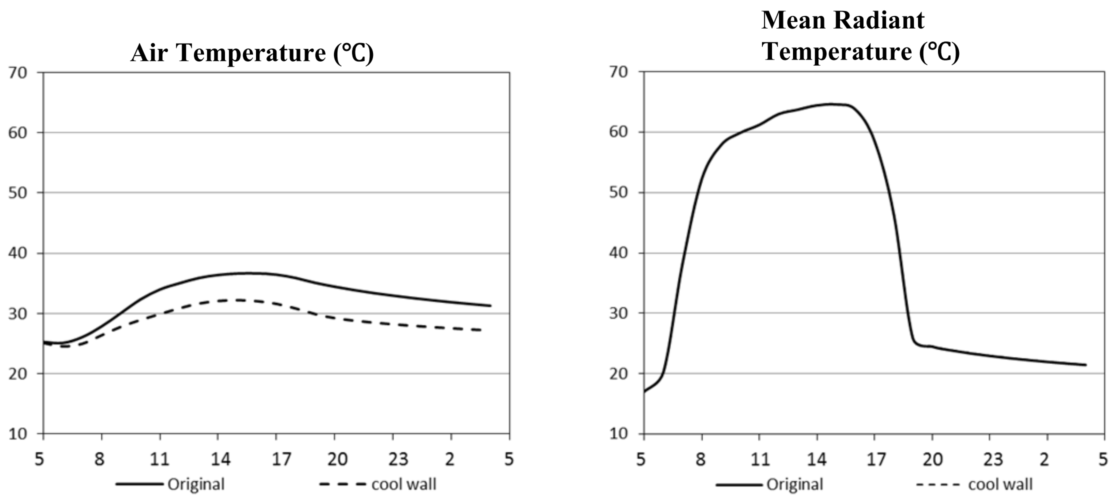


Figure 3. Averaged diurnal air temperature (Ta), and mean radiation temperature (Tmrt), 1.8m above the ground on a typical Summer day (from 5am, 22 July, to 4am the next day) in the selected area of Toronto, with two building wall types (Original: Heat Transmission 1.94 W/m²K; Cool Wall: 0.44 W/m²K).

Figure 2 compares Ta, Tmrt, and relative humidity with two roof types. Diurnal Ta and Tmrt with lower roof albedo are slightly higher than that with higher roof albedo, and relative humidity is lower for the model with lower roof albedo. The effect of roof albedo on Ta, Tmrt, and relative humidity is pronounced during daytime (from 11am to 7pm). During this period, Ta difference is around 0.2 ℃, Tmrt difference is around 0.06 ℃, and relative humidity difference is over 0.8%. At nighttime (after 7pm), the temperature difference between two models is close to 0℃. This is to say, the effect of roof albedo on community-scale thermal environment is mainly during daytime. Additionally, higher roof albedo could also reduce the surface temperature of buildings, leading to a higher indoor comfort, lower energy consumption, and lower heat emission. However, the impact of heat emission from indoor of buildings is not included in this simulation. Therefore, the environmental benefits of high albedo roof are even higher than the results shown by these simulations.

Figure 3 shows the comparison of Ta and Tmrt with two wall types. With the cool wall which is completely insulated, the amount of solar heat absorption is dramatically reduced. Lower heat capacity also leads to the lower heat release into the community environment. Compare to roof surface, wall surface is playing a more critical role of affecting thermal environment for residents walking on the street. With the cool wall, diurnal Ta is more than 4 ℃ lower than that with original building wall. The largest Ta differences are more than 5 ℃ that is observed in the evening, during 6pm to 9pm. Meanwhile, the Tmrt with lower heat capacity wall is slightly higher than that of original walls. The differences are between 0.02 ℃ to 0.04 ℃, which is close to 0 ℃. It is to say, reduce the heat transmission, in order to reduce the heat release in to the urban community is an effective method to reduce urban heat island and cool the urban community.

Discussion About Implication

Building surface with a high albedo could be achieved by cool coating. The intention of implication is to increase the irradiation reflection from building surface; the cool coating for building is equipped for exterior walls and roofs only. Since most roofs have regular maintenance schedules or are re-roofed or recoated periodically, in most applications, cool roofs incur no additional cost. In Los Angeles, it was demonstrated that applying a high-albedo coating to one house resulted in seasonal savings of 2.2kWh/day (80% of base-case use) [*Akbari et al. 2001*]. Some of the cool wall products must be installed by extensive expert trained laborer; cool wall might incur an extra initial cost. However, cool coating could reduce air conditioning load and eliminate the repainting cycle, it is more cost effective than traditional painting over time [*Smith 2011*]. According to the results from simulation, data based demonstration could provide the standard for related industries for new products investigation and development. The effects on UHI from building surface reflectivity is compared and analyzed in this research. Further research is needed to address issues such as type and level of wall insulation to discuss about the effects from heat conduction and heat capacity of building surfaces, as well as their retrofit cost.

Conclusion

The simulation study is carried out for demonstrating the environmental affects form building roof and wall performance. As the result, reducing building wall transmissions from 1.94 to 0.44 W/m²K, the urban Ta is reduced over 4 ℃. It is clear that building wall transmission is an important factor on urban heat island mitigation. This result provides a hint for urban climate change policy development.

As the cities sprawl in Canada, the urban climate change is becoming to be one of the major challenges. In this research, the effect of cool roof and cool wall on UHI mitigation is demonstrated by numerical simulation in these two cities provided policy-relevant data and analysis, which are not included in current policies. It helps develop evidenced based guidelines for specific UHI mitigation technique implement in the urban communities of Toronto and Montreal. This work addresses the effects improvement of understanding of heat island mitigation measures on urban air quality in cold climates with cool building surface installation.

This implement could be carried out gradually, according to the roof and wall's repainting cycle of buildings in the city. Related financial support from the government could be applied to encourage this installation.

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