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Comparing the effects of urban heat island mitigation strategies for Toronto, Canada

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ABSTRACT

Increasing awareness of the urban heat island (UHI) effect has raised attention about the outdoor thermal comfort in cities worldwide. Several studies in the last decades have revealed how critical the UHI effect can be in a cold climate, such as in Canadian cities. As a result, in Toronto, one of the cities experiencing the highest rate of building development in developed countries, UHI mitigation strategies are currently the object of extensive debates. This study evaluates different UHI mitigation strategies in different urban neighbors of Toronto, selected according to their building density. The effects of cool surfaces (on the roofs, on the street pavements or as vegetation areas) are evaluated through numerical simulations using the software ENVI-met. Having obtained the surface temperature, outdoor air temperature, mean radiant temperature, and physiologically equivalent temperature, this study compares the possible mitigation of net surface radiation and thermal radiative power. The results demonstrate that the duration of direct sun and the mean radiant temperature, which are strongly influenced by the urban form, play a significant role in urban thermal comfort. Finally, this research supports new policies for promoting sustainable urban development in Toronto, and suggests design strategies for a more resilient urban planning.

1. Introduction

Episodes of extreme heat are becoming more common worldwide, including in countries commonly considered cold, such as Canada. In 2005, residents of Ontario suffered a hot summer with long stretches of high temperatures and humidity; in particular, Toronto sustained 41 days with temperatures above 30 °C, and 25 nights with minimum temperature above 20 °C [1]. Due to climate change, a cold country such as Canada is likely to experience greater warming than many other regions. Climate models indicate that, due to the expected warming of up to 9 °C by the 2080s in the Arctic and the southern and central Prairies [2], the number of days with average temperatures above 30 °C is likely to increase in cities across Canada, and particularly in those located in the Windsor-Quebec corridor (such as Toronto) and portions of British Columbia.

The experienced climate change has already shown many health, environmental, and energy consumption implications. The heat wave that hit Chicago in 1995 killed between 550 and 800 people [3]; similarly, in Europe the death of 35,000 people was attributed to heat during the summer of 2003 [4]. Canadian deaths linked to heat are already substantial, although only a small number of them are certified as due to heat strokes [5,6]. Health Canada reported that in the seven biggest Canadian cities, when the daily average temperature is higher than 20 °C, the relative mortality increases by 2.3% for each degree increase in the air temperature. Similarly, a study in the Netherlands also demonstrated the impact of ambient temperature on mortality during 1979–1997 [96]. For each degree increase in the air temperature above the optimum, the total mortality increased by 2.72%. This means that a UHI intensity of 2–3 °C translates into a 4–7% increase in the mortality rate in Canada, and 5–8% mortality rate increase in Netherlands. Elevated air temperatures facilitate the chemical reactions that transform atmospheric nitrogen oxides and volatile organic compounds into ozone, one of the main components of urban smog [7,8]. Considering that over 70% of Canadians live in urban areas, and the many effects of global warming and UHI on electricity infrastructure, community safety and citizen wellbeing, it is clear why these topics are receiving considerable attention in Canadian policies interested by reducing the UHI effect in protecting both human health and urban environment [9].

The main factors that contribute to UHI are [10–13]: large surfaces of materials (mainly asphalt and concrete) with low albedo and high admittance; reduced vegetation and permeable surfaces,

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which limit shade and evapotranspiration; tall buildings and narrow streets that modify overall wind speeds, and create urban canyons; concentration of heat-generating activities released from fuel combustion (including cars), HVAC systems, and other anthropogenic processes.

1.1. Urban ground surface

Asphalt and concrete constitute as much as 40% of Canadian urban surface area [14,15]. On average, in Toronto, asphalt area is 16.2% and concrete area is almost 13.7%, to which should be added the roof top areas [16]; obviously these average values are much higher in downtown. Asphalt and concrete have low albedo, with values as low as 0.1 on average for asphalt and 0.3 or 0.4 for concrete [17]. As a strategy for mitigate the UHI, surface materials with high albedo and emissivity have been proposed worldwide since they remain cooler when exposed to solar energy [18–21].

1.2. Urban vegetation

Another important aspects of urban areas is that here the fraction of the ground covered by trees and other vegetation is smaller and contains less biomass than in nonurban areas. The absence of vegetation impacts the UHI in several ways, since vegetation, and in particular trees, intercept solar energy, and their shade reduces the temperature of surfaces below while increasing the latent heat exchange for the evapotranspiration process [22–26].

Vegetation have shown to cool the surrounding environment by reflecting more solar radiation (higher albedo compared to common pavements), by absorbing and accumulating less heat, while the evapotranspiration contributes to cool the environment [27–30]. Air temperature reductions due to vegetation of 20 °C in Tokyo, 5 °C in Singapore and 8 °C in Athens were reported [30,31].

1.3. Urban canopy

The urban form also plays an important role in the UHI, since a dense form generally is responsible for multiple reflections of solar energy, and influences the air convection out of urban canyons by influencing the wind "porosity" of the city [32–34]. Colucci and Horvat [35] investigated the solar access right in different neighbors of Toronto, and found that the built environment of the city is not designed to take full advantage of available solar energy [35]. The urban form influences the heat loss from within the urban canyons due to the lower sky view factor (SVF). Tall buildings and narrow urban canyons reduce the sky view factor (SVF) and increase the amount of shaded area at the surface, keeping the bottom of urban canyons cooler than the surrounding area by day, but increasing it at night time [36–40]. Computer modeling has shown that an urban form with a building height to street width around 0.5 and a building density around 0.3 should be promoted as measures to mitigate urban discomfort and other UHI effects [41]. Bosselmann et al. back in 1995, presented an extensive study of how the change in the urban from of downtown Toronto could affects sunlight on sidewalks and open spaces as well as the wind conditions at street level. That study started by recalling the advice of Thomas Jefferson about the importance of garden squares in North American cities in order to create natural cool air circulations between the gardens and built-up city blocks [42]. Bosselmann et al. focused on the wind velocities in Toronto by making wind tunnel measurements which confirmed that among several high-rise towers wind frequently and significantly accelerates above 10 m/s, creating both wind chilling effects and mechanical forces on the pedestrians that make it unsafe for them to walk.

1.4. Simulation studies on UHI mitigation

Evaluating the relationships between buildings and the surrounding outdoor environment for controlling the urban climate and outdoor thermal comfort, and for mitigating the UHI effect is a multidisciplinary task which requires competences in the subjects of landscaping, urban planning, architecture, building materials, and many others [43–46]. In view of the negative impacts of the UHI effects, in the last two decades, many researchers have focuse on the strategies for mitigating UHI by simulating single neighbors [16,42,47–49]. Preliminary results have shown the importance of urban design on the microclimate of outdoor spaces and urban canopy layers [50–52]. The effects of some detailed urban planning technologies, such as green roofs or urban vegetation have been demonstrated [30,53].

Akbari and Taha simulated the effect of reflective surfaces and trees in four Canadian cities (including Toronto) and found that by increasing the vegetative cover by 30%, the cooling-energy use in Toronto could be reduced by 10% in urban houses and 20% in houses located in suburban areas. Results also showed that by increasing the albedo of houses by 0.2 (from moderate-dark to medium-light color), the cooling-energy use can be reduced by about 30–40% [54]. More recently, Taleghani et al. showed that in the temperate climate of Portland (OR, USA) white material (with albedo above 0.9) increased the globe and mean radiant temperature (0.9 °C and 2.9 °C) and produced a cooler air temperature (1.3 °C) in comparison with a dark pavement [55,56]. In Shanghai, Yang et al. showed that by increasing the ground surface albedo by 0.4, the outdoor thermal comfort could be improved by up to 5–7 °C in the physiological equivalent temperature (PET) [57]. PET is defined as the air temperature at which the human energy budget is maintained by the skin temperature, core temperature, and sweat rate equal to those under the conditions to be assessed; this index is considered particularly suitable for outdoor thermal comfort [58], and has been extensively considered in recent urban microclimate studies [50,59,44]. Wang and Akbari used the thermal radiative power (TRP) in a block area in Montreal and showed that by changing the albedo of building roofs from 0.1 to 0.7, the TRP from roofs during the typical summer day decreased around 6–15% during 7 am to 5 pm, while the TRP from walls and ground decreased slightly. Moreover, also in the same block in Montreal, a change of the albedo of ground surface from 0.4 to 0.8 would decrease the TRP from ground around 4.0–9.6% during 9 am to 6 pm [49]. However, the adoption of highly reflective materials has also shown some negative effects both in facing buildings and for the pedestrian microclimate, which could receive unwanted reflections from the building facades. In Tokyo, for example, the use of high albedo materials on exterior opposite walls led to higher indoor cooling demands because of the increased solar radiation reflected from facing buildings [60]; as a consequence, the use of retro-reflecting materials has recently been proposed in urban canyons [61].

Several studies are reported by Bass et al. and Krayenhoff et al. about the impact of green roofs on Toronto's urban heat island by using mesoscale simulation [16,24]. Those studies integrate an urban surface parameterization model for taking into account the urban canopy layer originally proposed by some of the authors in a mesoscale meteorological model. High resolution land cover data (but still at the mesoscales of 5 km or 1 km) were used to represent the urban surface. Results suggested that the effects of 50% green roof or white roof (albedo raised from 0.15 to 0.60) coverage would be minimal, being less than 0.1 °C air temperature at 40 m above ground. These studies indicated that such UHI reduction strategies may have minimal effects far from the ground surface.

UHI mitigation strategies have generally been more studied in hot and dry cities, although UHI in cold cities is often more