Effects of increasing urban albedo in the Greater Toronto Area

Jandaghian Zahra' and Berardi Umberto2,*

1 Research Assistant, Department of Architecture Science, Ryerson University, Toronto, Canada
2 Department of Architecture Science, Ryerson University, Toronto, Canada
* uberardi@ryerson.ca

Abstract. Increasing surface reflectivity decreases the skin and air temperature, which potentially reduces cooling energy demands. The state of the art online numerical Weather Research and Forecasting model (WRF) is used to investigate the effect of increasing albedo in Toronto, Ontario, during the 2018 heat wave period (July 2nd through July 5th) on urban climate and building energy consumption. The study couples the WRF with a multi-layer of the Urban Canopy Model (ML-UCM) and Building Energy Model (BEM). The ML-UCM is a part of the land-surface parameterization to predict the heat and moisture fluxes from canopies to atmosphere. The BEM is coupled with Building Effect Parameterization to predict the energy consumption of buildings. BEM simulates the effect of heat generation from buildings on urban climate. The reflectivity of roofs, walls and roads are increased from 0.2 to 0.65, 0.60 and 0.45, respectively. Albedo enhancement leads to a decrease in air temperature by around 1°C and an increase in wind speed which induce a reduction in skin temperature. The combined effect of decreased solar heat gain by buildings and decreased air temperature reduced the energy consumption of HVAC systems by 3-5%, confirming the positive effect of increasing the albedo on urban climate.

1. Introduction

Heat waves have become more frequent since 1960s worldwide, including in countries commonly considered cold, such as Canada [1]. Urban area experiences warmer average temperatures than the surroundings. The average temperature in Greater Toronto Area increased continuously since the late 1800s. In Toronto, days with temperatures above 30°C are expected to increase from an average of 26 days in 1970s to 65 days by the end of 21st century [2]. Toronto Public Health determined that heat-related mortality averaged at 120 deaths per year, with predictions that it will double by 2050 and triple by 2080. Between 1970 and 2000, Toronto had an average over 3955 heating degree days (HDD) and 275 cooling degree days (CDD) [2].

Increasing heat waves lead to growing cooling energy demands and water consumptions, rising risks of asphalt melting, concrete hogging, and railway distortions [3]. The increment of heat wave is attributed to the effects of global climate change and local urban heat island (UHI). The main factors that contribute to the heat island effects are large surfaces of materials with low albedo and high emittance, reduced vegetation and permeable surfaces and concentration of heat-generation released from human activities, fossil fuel combustions and HVAC systems [4]. The UHI effects extend the frequency and duration of heat waves and induce local climate change. The impacts of the synergy between the UHI effects and heat waves are greater than the sum of its shares and thus urban areas are more vulnerable to heat waves compared to other regions and should be considered as a main focus to mitigate the heat island effects. Increasing urban albedo is a verifiable heat island mitigation strategy to decrease urban temperatures, photochemical reaction rates, and pollution, thus improving human health and comfort [5]. A study in Montreal showed that the beneficial contributions of albedo enhancement are a decrease in daily air temperature by 0.7°C, an increase in dew point temperature by 0.4°C and an improvement in heat stress indices by 3% that led to a decrease in heat-related mortality by nearly 4%
during two heat wave periods [6]. Increasing surface albedo in Sacramento, Houston and Chicago resulted in a decrease in daily air temperature by 2.3°C in urban areas [7].

The beneficial effect of using reflective coatings for roofs and pavements in urban areas on buildings’ energy consumption is discussed in several papers [8-9]. Taha et al. coupled a simple one-dimensional PBL model with a Building Energy Model (BEM) [10]. Akbari et al. studied the effect of increasing albedo on the energy saving in buildings [11]. They used a mesoscale model coupled with a photochemical model to update the weather data and study the energy consumption change of buildings. Results showed a 20% reduction in cooling energy consumption. Urban canopy models are also coupled with computational fluid dynamics models to calculate interactions of building energy and urban environment. Ashie et al., used this approach for Tokyo where the urban surface modification decreased the air temperature by 0.4-1.3°C and cooling energy by 3–25% [12]. One of the widely used BEM models is based on the research performed by Salamanca et al. [13]. The intent of this study is to investigate the effects of increasing urban albedo on urban climate and energy consumptions in buildings in Greater Toronto Area during the 2018 heat wave period (July 2nd through July 5th). In this regard, the simulations are performed for two scenarios: the CTRL, that albedo of all urban surfaces is 0.2, and ALBEDO, where the reflectivity of roofs, walls and roads is increased to 0.65, 0.60 and 0.45, respectively. The online Weather Research and Forecasting model (WRF) is coupled with the Multi-layer of the Urban Canopy Model (ML-UCM) and the Building Energy Model (BEM). A brief description of these models is presented in the methodology section.

2. Methodology

2.1. WRF simulation setup

Weather Research and Forecasting model (WRF) is applied for urban climate simulations. Toronto is the largest city in Canada, centred at the ~43.7ºN and ~79.3ºW. The horizontal domain of the simulations is composed of four two-way nested domains with a grid spacing of 9, 3, 1 and 0.333 km x km, respectively. Figure 1 shows the third and fourth simulation domains covering the Greater Toronto Area (GTA). The 51eta vertical level is telescopically defined to take full advantages of the urban parameterization. The initial and boundary conditions obtained from the North American Regional Reanalysis (NARR). The simulation is conducted during the 2018 heat wave period in GTA, started from the 2nd of July and lasted for four consecutive days. The results of the first 24hrs are disregarded as a spin up time. The land surface model NOAH-LSM provides skin temperature, surface sensible and latent heat fluxes. The Mellor-Yamada-Janjic scheme used Eta similarity theory to estimate the planetary boundary layer. The Rapid Radiative Transfer Model (RRTMG), Lin scheme, and Grell 3D is used for radiation, microphysics and cumulus models, respectively [14].

![Figure 1](image.png)

**Figure 1.** The 3rd (left) and 4th (right) domain of the Greater Toronto Area with LULC (black regions show the urban area and blue represents water body)

2.2. Building Effect Parameterization

The Multi-layer of the Urban Canopy Model (ML-UCM) calculates the impacts of a complex urban surface within their vertical mixing. Martilli et al. [15] developed the ML-UCM and Chen et al. [16] integrated it in mesoscale model. The ML-UCM is also known as the Building Effect Parameterization (BEP) that divides the urban canopy model into separate units and calculates the urban surface parameters (wall and roof temperature, heat fluxes, etc.) related to each unit. BEP tends to predict the vertical exchange of momentum, heat, and moisture and includes the conservation equation for Turbulence Kinetic Energy. The various building heights are considered and thus their shading effects
are estimated. The vertical perturbation from turbulence is assumed to have linear relation to the variation of mean value of properties in a grid. Thus, we followed the same approach developed by Salamanca et al. (2011) to consider the effects of urban canopy model and heat island mitigation strategy on urban climate simulations.

2.3. Building Energy Model
Building Energy Model (BEM) is used to provide a feedback from the urban structure to urban climate to consider the impacts of the heat emission from buildings on heat fluxes from the canopy. Using heating and cooling systems in buildings can increase the outdoor air temperature while regulating the indoor comfort. Modeling the energy consumption of buildings is a complicated process that uses different weather parameters (e.g., temperature, solar radiation, wind speed, relative humidity, etc.). Salamanca et al., [13] developed the BEM that can be coupled to WRF. The BEM calculates the cooling and heating energy demands for the air conditioning system of buildings as well as heat emission to the canopy. The inputs to BEM are air temperature, wind velocity, humidity, and the shortwave and longwave radiations from the mesoscale model. An algorithm is designed for energy consumption of the air conditioning system that can consider the comfort temperature and heating and cooling capacity of the HVAC system. The BEM estimates temperature of urban surfaces, heat and moisture fluxes from the urban area for the mesoscale model.

3. Results and Analyses
3.1. Simulation performance evaluation
The simulated 2-m air temperature (T2) and 10-m wind speed (WS10) are compared with the measurements obtained from weather stations across the GTA. The measured data are from Climate Canada Historical Data (http://climate.weather.gc.ca/). Figure 2 shows the geographical locations of selected weather stations the blue, red and orange circles represent Toronto City Centre (~43.37ºN and ~79.23ºW), Lester B. Pearson INTL Airport (~43.40ºN and ~79.24ºW) and Buttonville (~43.86ºN and ~79.37ºW), respectively. For statistical analysis of the simulation results, the Mean Bias Error (MBE), Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) are calculated for three days of the modeling. The MBE is the indication of underestimation or overestimation of the predicted meteorological variable compared to the measured data. The MAE illustrate the absolute error in simulation and the RMSE is a more rigorous indicator for model assessment [17].

![Figure 2. Geographical locations of weather stations in the GTA; the blue, red and orange circles represent Toronto City Centre, Lester B. Pearson INTL Airport and Buttonville, respectively](image)

3.1.1. Air temperature. Table 1 presents the performance metrics of 2-m air temperature (T2) in three selected weather stations in the GTA during the 2018 heat wave period. The model tends to underestimate the temperature in Toronto City Centre (MBE ~ -0.4ºC) and over-estimate it in Lester B. Pearson INTL Airport (MBE ~ 0.3ºC) and Buttonville (MBE ~ 0.7ºC). The main reason for T2 underestimation, in the downtown area with high residential and commercial intensity, is the miscalculation of anthropogenic heat emission in the WRF solver. Nevertheless, the average of MAE and RMSE (~1ºC) illustrate the model capability to predict the air temperature reasonably well, hence the results can further be applied to compare with albedo enhancement simulation. Figure 3 shows the hourly comparisons between simulation results and measurements. These comparisons indicate that
the model predicts the hourly 2-m air temperature more closely to measurements in urban area vs its surroundings.

Table 1. Mean Bias Error (MBE), Mean Absolute Error (MAE), and Root Mean Square Error (RMSE) of 2-m air temperature (°C) in GTA during the 2018 heatwave period

| Station Name              | MBE (°C) | MAE (°C) | RMSE (°C) |
|---------------------------|----------|----------|-----------|
| Toronto City Centre       | -0.43    | 0.77     | 0.98      |
| Lester B. Pearson INTL Airport | 0.30    | 0.97     | 1.52      |
| Buttonville               | 0.75     | 1.79     | 2.06      |
| Average                   | 0.12     | 1.18     | 1.52      |

Figure 3. The time series (hourly) of the simulated (solid line) vs. measurements (dashed red line) of 2-m air temperature (°C) at three weather stations across GTA during the 2018 heat wave period, the Y-axis is air temperature (°C) and the X-axis is time (hour).

3.1.2. Wind speed. Wind speed plays an important role in calculation of air temperature from skin temperature in land surface model. The transient effect of wind speed on air temperature is complicated; an increase in wind speed increases the convection heat transfer that reduces the skin temperature, which simultaneously causes a decrease in convection heat transfer. The averaged MBE (~0.52 m/s), MAE (~1.6 m/s) and RMSE (~2.1 m/s) indicated that the model slightly overestimates the wind speed especially in urban area.

3.2. Effects of increasing surface albedo
We conducted two sets of simulations with different scenarios concerning urban surface modifications: the base case condition that the reflectivity of urban surfaces is assumed to be 0.2 (CTRL); and the increasing surface albedo scenario where the reflectivity of roofs, walls and roads is increased to 0.65, 0.60 and 0.45, respectively (ALBEDO). Results discussed here are based on the comparison between the ALBEDO and CTRL scenarios for selected weather station in the GTA during the 2018 heat wave period. The averaged reduction in 2-m air temperature is about 1°C and the decrease is more noticeable in Toronto City Centre around noon and early evenings (Table 2). Figure 4 displays the hourly 2-m air temperature differences between CTRL (dashed black line) and ALBEDO (blue solid line) scenarios. The maximum decrease of air temperature is about 2°C in the urban area of the GTA around noon. The albedo enhancement affords a slight increase in wind speed over the domain.

Table 2. The differences between CTRL and ALBEDO scenarios of T2 (°C) and WS10 (m/s) in the GTA during the 2018 heatwave period

| Δ T2 (°C) | Δ WS10 (m/s) |
|-----------|-------------|
| Toronto City Centre | 1.00 | 0.88 |
| L.B.P INTL Airport    | 0.88 | 0.81 |
| Buttonville            | 0.33 | 0.02 |
| Average                | 0.81 | 0.02 |
3.3. Energy consumption in buildings

The peak energy consumption of HVAC systems occurs around noon and in the evening of all days because of the building thermal mass. The maximum energy is about 6W/m² on the hottest day and the minimum energy is negligible during nighttime. Increasing the albedo can decrease the energy consumption of HVAC systems by reducing the solar gain from roofs and reducing ambient temperature.

![Figure 4](image-url)

**Figure 4.** The hourly 2-m air temperature differences between CTRL and ALBEDO scenarios during the 2018 heat wave period in three weather stations; Toronto City Centre (black solid line), Lester B. Pearson INTL Airport (blue solid line) and Buttonville (red dashed line)

The average decrease in energy is about 0.7W/m² and the maximum decrease in energy is 1.4W/m². Figure 5 shows the energy consumption in buildings in GTA during the three-day heat wave period. Typically, energy savings in HVAC systems would improve the air quality by reducing the anthropogenic emission from power plants and HVAC operations. In the case of Toronto, almost 99% of the electricity is generated by clean energy such as nuclear power plants, hydropower plants and wind turbines. Hence, in our specific case, energy savings in HVAC operations has a minimal effect on anthropogenic emission of the region. Overall, increasing surface reflectivity of roofs and walls reduce the cooling energy demand by around 3 to 5% in the GTA during the 2018 heat wave period. But further analyses are required to study the impacts of albedo enhancement on HVAC energy consumptions throughout a year.

![Figure 5](image-url)

**Figure 5.** Energy consumption of HVAC systems of buildings (solid black line) and the differences between CTRL and ALBEDO (dashed red line) in GTA during the three-day of 2018 heat wave period

4. Conclusion

The WRF is coupled with the ML-UCM and BEM to investigate the effects of increasing urban albedo on urban climate and HVAC energy consumptions in buildings in GTA during the 2018 heat wave period. The model performance is evaluated by comparing the simulation results with measurements obtained from selected weather stations across the domain. The comparisons indicated the model capability in predicting meteorological parameters and thus is mostly suited for application of simulating and investigating the effects of urban heat island and its mitigation strategies. The model, as configured here, captures well the diurnal variations of 2-m air temperature (MBA ~ 0.12°C), and slightly overpredicts 10-m wind speed (MBA ~ 0.52 m/s).
Two sets of simulations are conducted with regard to surface modifications: CTRL scenario and ALBEDO scenario. The albedo of roofs, walls and roads are increased from 0.2 in CTRL case to 0.65, 0.60 and 0.45 in ALBEDO case, respectively. The air temperature decreased during the simulation period, with the maximum hourly decrease of about 2°C and an average of nearly 1°C across the domain of interest. The wind speed slightly increased in the GTA during the heat wave. Increasing surface albedo can decrease the energy consumption of HVAC systems by an average of about 0.5W/m². The maximum energy savings in HVAC systems operation is close to 1W/m². Overall, the cooling energy demand decreased by around 3 to 5% in the GTA during the 2018 heat wave period.

The results presented here are episode- and region-specific and confirmed that the albedo enhancement is an effective mitigation strategy to reduce the air temperature and thus improve air quality in the GTA. These findings are an asset for policy makers and urban planning designers. However, we suggest studying the effects of other UHI mitigation strategies on urban climate prior to applying any surface modifications. We recommend a simulation for the entire year that can reveal more information of the mitigation strategy impacts on HVAC energy consumptions in buildings.

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References

[1] USGCRP.- U.S. Global Change Research Program. 2017. Climate Science Special Report: Fourth National Climate Assessment, Volume I.
[2] CDC.- U.S. Centers for Disease Control and Prevention. 2016. Compressed mortality file, underlying cause of death. CDC WONDER database.
[3] Akbari H, Pomerantz M, Taha H. 2001. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. Solar energy, 70(3): 295-310.
[4] Zuo, J., Pullen, S., Palmer, J., Bennetts, H., Chileshe, N., and Ma, T. 2015. Impacts of heat waves and corresponding measures: a review. J. Cleaner Production, 92: 1-12.
[5] Kalnay, E., and Cai, M. 2003. Impact of urbanization and land-use change on climate. Nature, 423: 528-531.
[6] Jandaghian, Z., and Akbari, H. 2018. The effects of increasing surface reflectivity on heat-related mortality in Greater Montreal Area, Canada. Urban Climate. 25: 135-151.
[7] Jandaghian, Z., and Akbari, H. 2018. The effects of increasing surface albedo on urban climate and air quality: a detailed study for Sacramento, Houston and Chicago. Climate. 6: 2-27.
[8] Hart M, Sailor D. 2009. Quantifying the influence of land-use and surface characteristics on spatial variability in the urban heat island. Theor Appl Climatol, 95(3-4): 397-406.
[9] Santamouris M. 2014. Cooling the cities-A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. Solar Energy, 103: 682–703.
[10] Taha, H., Akbari, H., Rosenfeld, A. and Huang, J., 1988. Residential cooling loads and the urban heat island the effects of albedo. Building and Environment, 23(4): 271-283.
[11] Akbari, H. and Konopacki, S., 2005. Calculating energy-saving potentials of heat-island reduction strategies. Energy Policy, 33: 721–756.
[12] Ashie, Y., Ca, V. T. and Asaeda, T., 1999. Building canopy model for the analysis of urban climate. Journal of Wind Engineering and Industrial Aerodynamics, 81: 237-248.
[13] Salamanca, F., Krpo, A., Martilli, A. and Clappier, A., 2010. A new building energy model coupled with an urban canopy parameterization for urban climate simulations—part I. formulation, verification, and sensitivity analysis of the model. Theoretical and Applied Climatology, 99: 331–344.
[14] NCAR. WRF User’s Guide; Mesoscale & Microscale Meteorology Division; National Center for Atmospheric Research (NCAR): Boulder, CO, USA, 2016.
[15] Martilli, A.; Clappier, A.; Rotach, M., 2002. An urban surface exchange parameterization for mesoscale models. Bound. Layer Meteorol, 104: 261–304.
[16] Chen, F., et al. 2011. The integrated WRF/urban modelling system: development, evaluation, and applications to urban environmental problems. International Journal of Climatology, 31: 273–288.
[17] Jandaghian, Z., Touchaei, A.G., and Akbari, H. 2017. Sensitivity Analysis of Physical Parameterizations in WRF of Urban Climate Simulations and Heat Island Mitigation in Montreal. Urban Climate. 24: 577-599.