Mitigating the Urban Heat Island with Green Roof Infrastructure

Brad Bass,
Adaptation & Impacts Research Group
Environment Canada at the University of Toronto
Institute for Environmental Studies

Scott Krayenhoff, Alberto Martilli, Roland Stull
Department of Earth and Ocean Sciences
University of British Columbia

Abstract

Green roof infrastructure is a technology that allows the use of vegetation to reduce rooftop temperatures. The purpose of this study was to assess the degree to which green roof infrastructure could reduce the urban heat island in the City of Toronto. The Mesoscale Community Compressible (MC2) model was run in conjunction with the ISBA SVAT scheme and an urban canyon model at a 1 km resolution for 48 hours with the boundary and initial conditions for June 27-29, 2000. The temperatures in the lower boundary layer were compared for the base case and the case with green roofs, covering 5% of the total landmass. When green roofs in high-density areas were provided with sufficient moisture to drive evapotranspiration, temperatures across the city were reduced between 1 – 2 ^{o}C at 1300 hours (but wasn't the difference between the greenroofs with moisture and the plain moisture more on the order of a 0.3 ^{o}C reduction city-wide with a smaller band of 1 ^{o}C cooling?) . Limited green roof coverage in an urban area was found to intensify the cooling that could be provided by similar vegetation in the core (I don't quite understand what this sentence is saying).

Introduction

The urban heat island is primarily due to the replacement of the natural landscape with hard, non-porous surfaces that are typical in most cities. Vegetation provides a source of moisture for evapotranspiration, the movement of water back to the atmosphere as water vapour. Greater partitioning of the absorbed solar energy into evapotranspiration reduces the amount of energy stored in urban materials and released as heat, thereby reducing the temperature of the vegetated surface and the low-level air. Energy used for evapotranspiration is transformed into latent heat, because it is only released as heat when the water vapour molecules condense back into water, as they are cooled in the upper atmosphere. Hard, non-porous surfaces not only absorb most of the incoming solar energy and reradiate it as heat, but they do not allow water from rain events to be absorbed, water that would evaporate and thus convert some of the solar energy into latent heat.

A comparison of several types of surfaces, from a study done in Oregon (Luvall and Holbo, 1989) indicates the potential surface temperature differences that can be observed, even in an urban area (Figure 1). Note that the temperatures of the road and the clear-cut areas range between 45 and 60^{o}C, and for the most part are above 50^{o}C. The surface temperatures of the forest, the shelter wood and the dougas fir (DF) plantation are all below 30^{o}C and the grassland, not shown in the diagram, is also in this range (Luvall and Holbo, 1989).

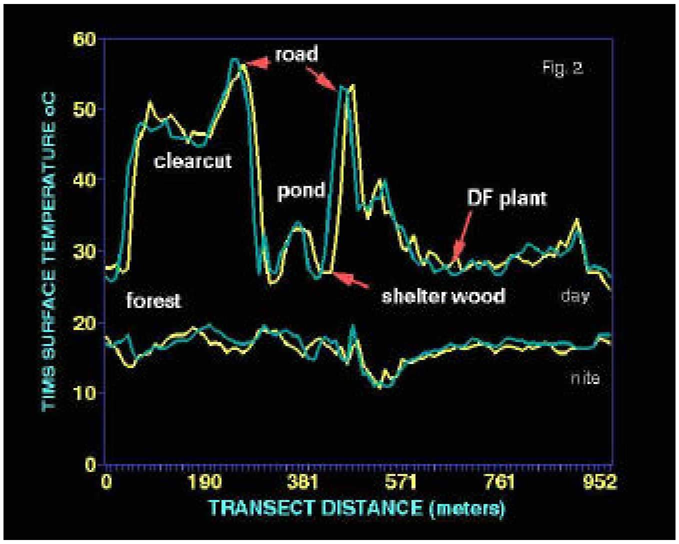


Figure 1. Surface temperature transect, Model Forest, Oregon (courtesy of Jeff Luvall, Marshall Space Flight Centre, NASA)

Although this data supports an urban forestry strategy, rooftops may play a vital role in reducing the urban heat island (UHI). The UHI exists in different layers, one of them being the urban boundary layer, the layer of the atmosphere extending roughly from rooftop level up to the level where the urban influence is no longer "felt" (e.g. Oke, 1976). Temperatures in the boundary layer can impact temperatures at canopy level, i.e. the level where most people live, and the chemistry of the boundary layer, which in turn affects the severity of certain pollution events. Rooftops, particularly flat roofs at high elevations, do affect this layer. The true colour and thermal imagery of Baton Rough, La. indicate that rooftops are some of the warmer surfaces in the city (Figure 2).

Rooftops should be considered for other reasons as well. Warmer roof temperatures increase the UHI but also allow more heat into a building than cool roofs, elevating temperatures in homes and one and two story buildings, and in the top floor dwellings and offices. These higher temperatures, at a minimum, increase the thermal discomfort of residents but can also place inhabitants with respiratory and heart disease at higher risk. The increased temperatures also increase the peak loads needed to meet the requirements for air conditioning and refrigeration, which in turn can lead to increased emissions of greenhouse gases, nitrous oxides and other pollutants.

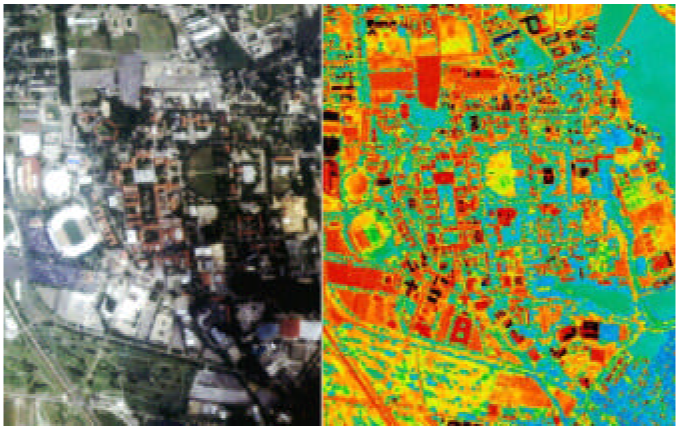
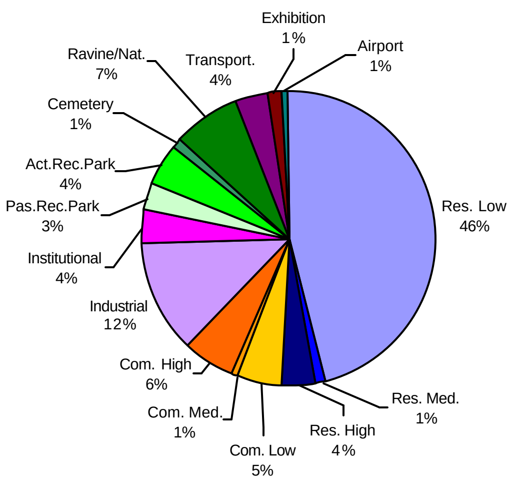
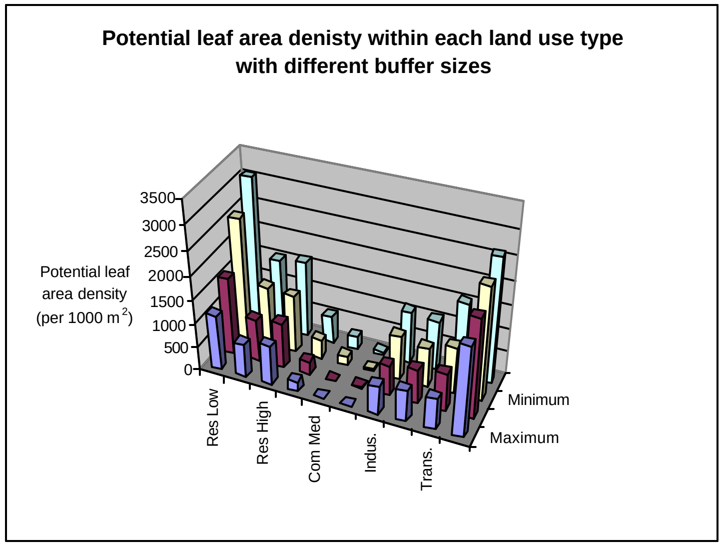


Figure 2. True-colour and thermal imagery of Baton Rouge, La (courtesy of Jeff Luvall, Marshall Space Flight Centre, NASA).

A chart of land use in the City of Toronto, before amalgamation in 1998, suggests that much of the city consists of low-density residential housing, and would support a ground-level vegetation program (Figure 3). To some extent this is true, but upon examination of one such indicator of urban forestry potential, leaf-area density (Figure 4), even minimal zoning restrictions can substantially reduce the potential for urban forestry, while maximum can reduce this potential by approximately two-thirds (Duffy, 2000). Thus other space in the city must be brought into cultivation to pursue an urban revegetation strategy.

Green roofs also bestow several other benefits, both to the building and the urban environment. They mitigate the extreme swings in temperature experienced by the roof membrane, extending the life of this piece of the building envelope. For the building, particularly small buildings, they reduce energy consumption in both winter and summer; they provide green amenity space for the building inhabitants and space for gardening or horticultural therapy. Public benefits include the reduction of stormwater runoff and combined sewer overflow (CSO), the flushing of the sewer system during heavy rain events that overwhelm the capacity of a city's drainage infrastructure. CSO is one of the most pressing environmental issues facing North American municipalities. Other public benefits include improved air and water quality, increased habitat for wildlife and increased food security.





Figures 3 and 4. Distribution of land use and restrictions on zoning in Toronto

Modelling the Urban Heat Island and Green Roof Infrastructure

The UHI has a horizontal scale of several tens of kilometers, roughly 2-3 times the city size, and it can interact with and modify specific types of atmospheric circulation such as lake breezes or mountain flows which operate at a similar or slightly larger scale. The most appropriate numerical model to assess the impact of green roof infrastructure on the UHI, must be able to resolve circulation at this scale, the "mesoscale in meteorology. For this reason the Mesoscale Compressible Community Model (MC2, Benoit et al. 1997) was used in this research. The model solves the Navier-Stokes set of equation in the non-hydrostatic, compressible form with a semi-implicit, semi-lagrangian numerical scheme. Details on the physical parameterization can be found at:

http://weatheroffice.ec.gc.ca/cmc_library/data/PREVISIONS /physic98.pdf.

For natural areas in and around the city, the fluxes from the surface were parameterized by (ISBA), a soil-vegetation-atmosphere transfer (SVAT) scheme (Noilan and Planton, 1989).

There are two ways to simulate the fluxes from urban land use to a mesoscale model. One method would treat the urban land use as a natural terrain, using ISBA, but with adjustments to the roughness length to approximate building elevations. In this study, a more detailed parameterization was used to simulate the fluxes from the urban land use (Martilli et al., 2002). This parameterization accounts for the drag of buildings on atmospheric flow, turbulent kinetic energy enhancement and sensible heat storage and turbulent fluxes induced by the trapping of infrared and solar radiation in the urban canopy. Energy budgets are considered for roofs, walls, roads, and parking lots. The simulated short and long wave radiative fluxes also account for the shadowing, multiple reflection, and reduced sky view factor effects of the street canyon elements (Figure 5).

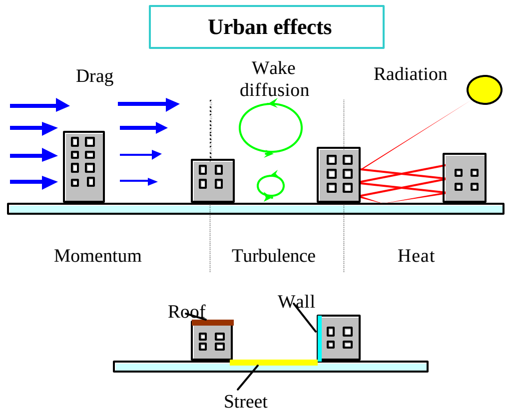


Figure 5. The effects of urban canyons on the atmosphere.

The fluxes from streets, walls, roofs and parking lots are averaged with the fluxes from the vegetated areas for each 1-km grid cell and injected into the lowest vertical level of the MC2 model above the surface. In this simulation, the surface is either a rooftop or the ground, depending on the land use. In grid cells with a mixed land use, the temperature produced by the model at 5m is closer to an average between the temperature at 5m above roof and the temperature at 5m above the ground.

The use of the canyon model, while providing a more realistic picture of how these fluxes are generated in a city, restricted the way in which green roofs could be represented in the model. When a roof was greened, and in this simulation the green roofs were composed solely of grass, the effect of that part of the building was removed from the model. This representation of green roofs may not be too egregious, but in order to avoid the removal of any building's impact, no more than one-half of any particular roof was greened in any simulation run. The model simulates the effects of urban canyons for different building heights, i.e. 10 metre high canyons, 20 metre high canyons, 100 metre high canyons, etc. Thus the distribution of building heights is an important input parameter, one that might affect the model results and a potential contributor to the uncertainty in this study as this distribution had to be estimated from other data sources.

The land use data was derived from commercially available data sets and specific site samples. It was interpolated to create percents of building, asphalt, concrete and natural areas for each 1 km^2 grid cell in Toronto. In each grid cell, the area of roof coverage was assumed to be equal to the area of road coverage. The green roof coverage was assumed to cover no more than 5% of total land use and was spread evenly throughout the city. As land use data were not available for the cities that border Toronto, a 10-km band of decreasing urban land use was created on the border mirroring the land use in the neighbouring Toronto grid cells. The remaining land use for this domain was taken from RPN, although its accuracy for this type of modeling is questionable, and it may have contributed additional uncertainty to the results.

It may appear that mesoscale simulations are disadvantageous for modelling climatic phenomena in urban areas because of the limitations in representing the city and the restriction of output to the boundary layer. However, mesoscale models account for the interactions with the rural surroundings and account for the impact of the larger scale, synoptic circulation patterns that determine the day-to-day weather. Nakamura and Oke (1988) found that temperatures in the urban canyon and temperatures above the canyon, i.e. in the lower part of the urban boundary layer, are usually very similar. Although generalizations of such site-specific results is risky, it is possible that the temperatures that were simulated at 5 m above the surface, the lower boundary layer, may indeed be very close to the temperature in the canopy layer.

For this study, MC2 was run over three different domains, each nested in the other, and each consisting of a 151 x 151 grid. The largest domain covered much of North America, and each grid cell was representative of a 625 km^2 area. Nested in this simulation was a simulation over the Great Lakes region, where each grid cell was representative of a 25 km^2 area, and nested into the Great Lakes domain was a domain with 1 km^2 grid cells that included the City of Toronto. A 1km2 resolution was the best compromise between the precision needed to represent an urban area and the CPU time needed to simulate a domain large enough to resolve the mesoscale circulation patterns. The vertical resolution was 10m in the lowest 5 numerical levels, and it was stretched up to 8232 m. The North American run was initiated at 19:00 hours on June 27, 2000, eastern standard time and ran for 48 hours. Boundary conditions were available every six hours.

The Great Lakes simulation was initiated six hours later. The output of the North American simulation was used to update boundary conditions every two hours. The Toronto simulation was initiated at 07:00 on June 28, and the boundary conditions were updated every hour from the Great Lakes simulation. All model runs finished on June 29, at 19:00 hours.

Results for June 29, 2000

Simulations have been run for three 48 hour periods in May, June and August. All simulation results compare reasonably well with surface observations at Pearson and Buttonville airports. The results are presented for 1300 hours on June 29, 2000. Due to the prevailing synoptic pattern, the City of Toronto as well as the surrounding areas were experiencing warm temperatures. The temperature and wind patterns for the City of Toronto indicate that except for a small area by the lake, these high temperatures were experienced throughout the whole city (Figure 6). However, there was a decrease in temperatures along a north-south transect, likely due to the increasing amounts of vegetation in each grid cell as one moves further north away from the downtown core.

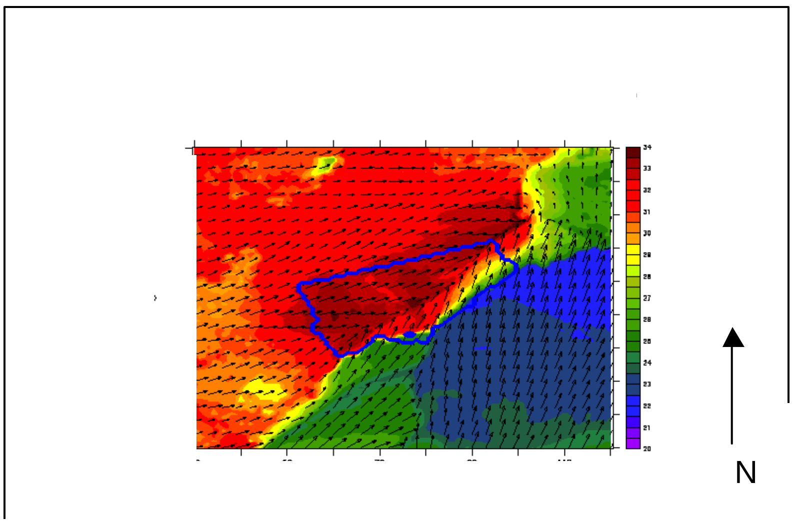
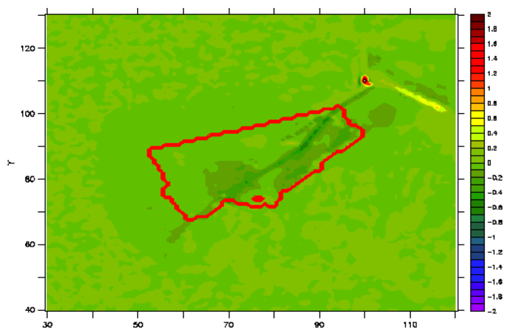


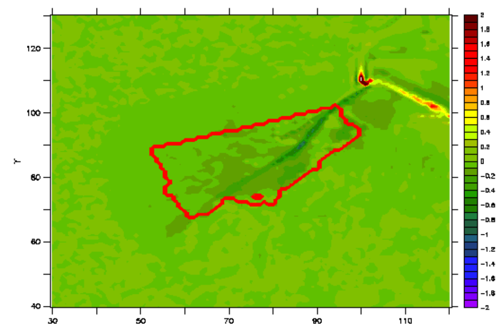
Figure 6. Temperature and winds, 29-06-00,1300 hours (Toronto within blue boundary).

The first green roof simulation produced a mild cooling over part of the city, on the order of 0.5^{o}C, concentrated in the area where the winds converge along a south-west – north-east transect (Figure 6). A similar pattern was observed for a simulation of white roofs, with an albedo of 0.6, although the cooler area was somewhat different and slightly larger (Figure 7). Further examination of the model output indicated limited soil moisture availability for that day, which would limit evapotranspiration for that day, and hence the potential cooling.

To better assess the potential of green roof cooling, the green roofs located primarily in the commercial and residential high-density areas were irrigated. Before the roofs were irrigated, the impact of irrigating just the existing grass at ground level was simulated (Figure 8). This produced a very pronounced cooling pattern in the lower boundary layer, on the order of 1 – 1.5^{o}C, although it was located in northwest of the high-density areas, probably due to the prevailing wind patterns. In one small area, near the lake, the temperature increased. When irrigated green roofs were added to these high-density areas, the cooling was intensified, reducing temperatures by as much as 2^{o}C and increasing the amount of area being cooled (Figure 9).

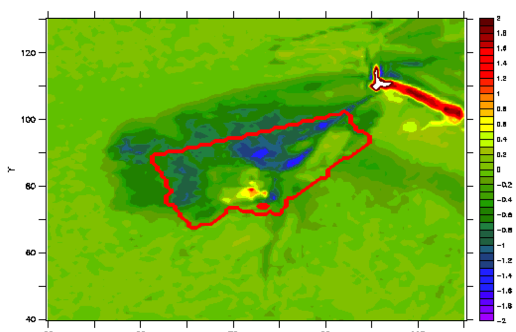


Temperature Change with Green Roofs
1300 Hrs, June 29, 2000

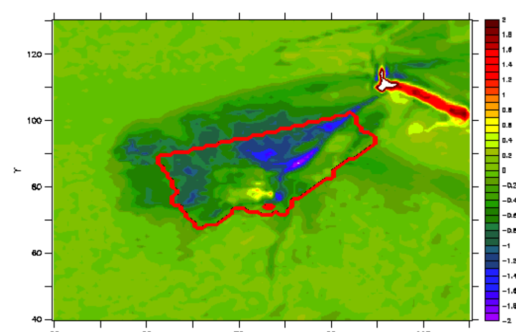


Temperature Change with White Roofs
1300 Hrs, June 29, 2000

Figures 6 and 7. Temperature change with green and white roofs (a = 0.6)



Temperature Change with Green Core - Evapotranspiration
1300 Hrs, June 29, 2000



Temperature Change with Green Core & Roofs- Evapotranspiration
1300 Hrs, June 29, 2000

Figures 8 and 9. Temperature change with irrigated core and irrigated core plus green roofs

Conclusions

This research is a first stage in assessing the impact of a green roof strategy on the urban heat island. The study combined MC2, running a 1-km simulation for the City of Toronto with a SVAT model and an urban canopy model to determine the fluxes of heat, moisture, momentum and mass to the atmosphere. The simulated temperatures in the lower boundary layer of June 29, 2000 compared well with the temperatures at the two airports in the Greater Toronto Area. In a simulation of the UHI in Toronto, a limited green roof strategy, consisting of grass roofs accounting for only 5% of the total area of the city, reduced temperatures in the lower boundary layer by up to 0.5^{o}C. Similar results were obtained for the same degree of white roof coverage, with an albedo of 0.6.

Irrigating the grass areas in the high-density areas produced a much more pronounced cooling effect. Adding irrigated green roofs in the high-density areas intensified and extended the cooling effect, creating areas that were 1-2^{o}C cooler than in the base case. Thus a limited green roof coverage, in combination with some of the existing green areas in the city is effective in reducing the temperatures in the lower boundary layer. As the model treats existing grass areas and green roofs in similar manner, the results also suggest that if existing grass areas in the city's core were replaced with green-roofed buildings, the cooling effect would not be diminished. However, this interpretation does not account for the effects of the building walls on urban climates.

In the white roof simulation, only the rooftop albedo was changed, but the whole building was left in the model, whereas with a green roof, the model removed that part of the building, and hence its impact the boundary layer, from the simulation. However, given the fact that the first green roof simulation and the white roof simulation were similar suggests that this representation of green roofs may not be a large approximation on a citywide scale.

References

Benoit, R., M. Desgagne, P. Pellerin, S. Pellerin, Y. Chartier and Desjardins, S., 1997: The Canadian MC2: A Semi-Lagrangian, Semi-Implicit Wide-Band Atmospheric Model Suited for Fine-Scale Process Studies and Simulation. *Mon. Wea. Rev.*, Vol 125.

Luvall JC and Holbo HR (1989) Measurements of short term thermal responses of Coniferous forest canopies using thermal scanner data, *Remote Sens. Environ.*, 27, 1-10.

Nakamura, Y., and Oke, T.R., 1988: Wind, Temperature and Stability Conditions in an East-West Oriented Urban Canyon. *Atmos. Environ.*, **22**, 2691-2700.

Martilli, A., Clappier, A., and Rotach, M. W., 2002: An urban surface exchange parameterization for mesoscale models. *Boundary-Layer Meteor.* (in press).

Noilhan, J., and Planton, S., 1989: A Simple Parameterization of Land Surface Processes for Meteorological Models. *Mon. Weather Rev.*, **117**, 536-549.

Oke, T.R., 1976: The Distinction Between Canopy and Boundary-Layer Urban Heat Islands. *Atmosphere*, **14**, 268-277.