

Chapter 322

Interaction Between the Urban Heat Island Effect and the Occurrence of Heatwaves: Comparison of Days with and Without Heatwaves



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Abstract In this study, the synergistic interactions of the urban heat island effect and the heatwaves occurring in the summer of 2018 in the cities of Montreal and Ottawa, Canada, are discussed through a comparison between days with and without a heatwave event. Three (3) time frames were prepared as part of this comparison: a pre-heatwave period from June 24 to June 29, 2018 (6 days); a heatwave period from June 30 to July 05, 2018 (6 days); and a post-heatwave period from July 06 to July 11, 2018 (6 days). The urban climates of these two cities were simulated using a Weather Research and Forecast (WRF) model at a grid resolution of 1 km; the urban heat island intensity was calculated using two methods: (i) calculating the temperature difference between urban and rural grid cells at a distance ranging between 3 to 10 km to the boundary of the urban area; (ii) using the “urban increment” method by which the temperature of urban grid cells are compared to the results of another simulation having all the urban land cover replaced by cropland. The diurnal evolution of several near-surface variables was compared throughout these three periods, including the ground surface temperature, the 2-m air temperature, relative humidity, and the 10-m wind speed.

Keywords Urban heat island · Weather Research and Forecast (WRF) · Heatwave · Extreme heat event · Heat wave-UHI synergy

322.1 Introduction

The changing climate and rapid urbanization have significantly changed the urban environment with more extreme weather conditions and elevated temperatures in an

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urban area. Several studies have adopted high-resolution numerical climate models to investigate the physical interactions between heatwaves and urban heat islands (UHI). Ramamurthy et al. (2017) analyzed the UHI in New York City during a heatwave with a 1 km resolution Weather Research and Forecast (WRF) model (Skamarock et al. 2019), and they found that the UHI increased by 1.5–2 °C during the heatwave episodes. Similar results can be found in the study by Li and Bou-Zeid (2013), which adopted the data from both observations and WRF simulations to quantify the UHI in the Baltimore area during the heatwave in 2008. They found the synergistic interaction of heatwave with UHI intensifies the temperature difference between urban and rural areas, resulting in a higher heat impact in cities. Ramamurthy and Bou-Zeid (2017) extended their studies to seven (7) cities in the U.S., and they argued that the amplitude of UHI is related to the physical size of the city, and the conditions can be quite different between different cities. The study by Chew et al. (2020) investigated the synergy effect between heat waves and UHI in the tropical coastal city, Singapore, and they notified that heatwave did not necessarily enhance the UHI effect. A recent review by Kong et al. (2021) suggested the necessity to investigate the interaction between the UHI and heatwave in the cities of different regions and climate zones which helps to explain the mechanism of the extreme weather conditions in an urban area and provide insights for the mitigation of overheating in cities. However, the interaction between UHI and heatwaves in cool climate regions such as Canada still needs more study.

322.2 Methods

An extreme heat spell event was recorded between 30 June–6 July 2018 in the joint region of Quebec and Ontario in Canada, with around 100 deaths (ECCC 2018). Most of the deaths were found in the urban areas because of the amplified heat stress for the urban residents due to UHI. To investigate the interaction between UHI and the heatwave that happened in 2018, a regional climate model was developed using the WRF model (Skamarock et al. 2019) with a high-resolution of 1 km for the analysis of the two major cities, Montreal and Ottawa, in the area. The configuration of the WRF model can be found in our previous studies (Gaur et al. 2020; Shu et al. 2022) with a detailed description and a validation of the results.

Two urban heat island intensity (UHII) calculation methods are considered and compared in this study. The first one is the “rural-ring” (RR) method, which identifies the rural area (RURAL) as a buffer region from 3 to 10 km distance to the edge of the urban area (URBAN) following the method described in the study by Yao et al. (Yao et al. 2019) (Fig. 322.2 a, b), then the UHII is calculated with temperature averaged over the urban and rural areas:

$$UHII_{RR} = T_{URBAN} - T_{RURAL} \quad (322.1)$$

Fig. 322.1 Study area and domains in WRF simulation

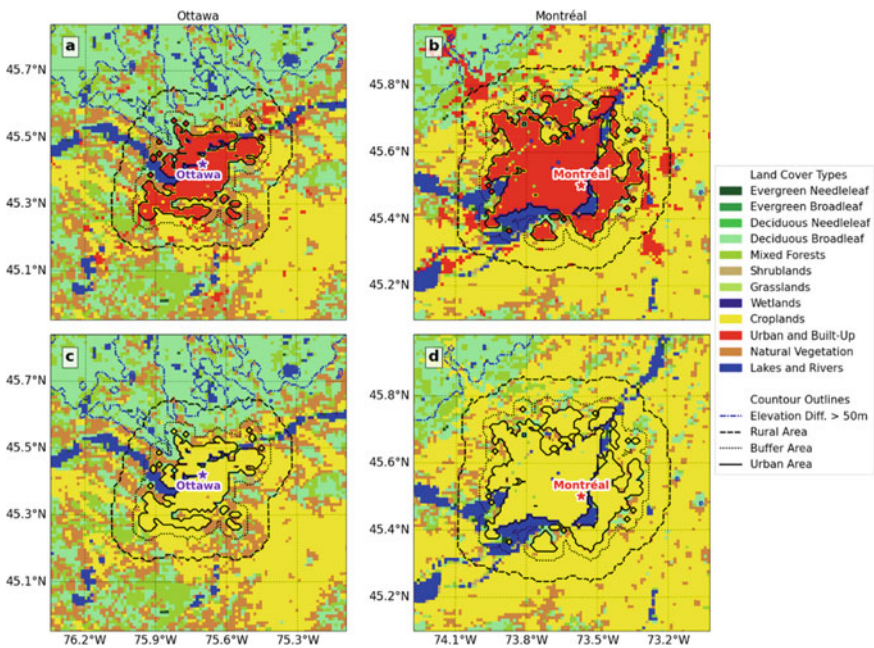


Fig. 322.2 Land use and land cover surrounding the two cities, **a** Ottawa, **b** Montréal and the urban and rural areas defined for urban heat island calculation using the “rural-ring” method, the urban land cover is replaced with croplands in **c**, **d** for the calculation of urban heat island using the “urban-increment” method

The second method is the “urban-increment” (UI) method, which needs to run a baseline case by replacing the urban land cover in the innermost computational domain with croplands (CROPS), then the UHII can be calculated by the temperatures averaged over the URBAN and CROPS areas from the two simulated cases:

$$UHII_{UI} = T_{URBAN} - T_{CROPS} \tag{322.2}$$

So, the UI method helps to identify how urbanization changed the natural climate because of the changes in land use, whereas the RR method indicates the real UHI by comparing the urban to the rural area in its neighbour.

322.3 Results

Figure 322.3 shows the spatial averaged air temperature profile of different areas from June 24 to July 11. The heatwave period (DUR) is the period from 30 June to 6 July, the pre-heatwave (PRE) is from June 24 to June 29, and the post-heatwave (POS) is from July 06 to July 11, 2018. The three (3) time frames (DUR, PRE, and POS) are defined with the same length of 6 days to eliminate the possible impacts of the seasonal variations. Both cities have significantly higher air temperatures during the heatwave. The maximum temperature of the six days all exceeded 30 °C, even for the RURAL and CROPS areas. It can be noticed that the temperature of the CROPS area is significantly lower than the temperature of the URBAN area, and the air temperature of the RURAL area is only slightly lower than that of the URBAN area most of the time. This suggests that the urban land cover does not only raise the air temperature in the urban area but also affects the rural lands in its surroundings. This also implies that the UHII calculated using the UI method would be higher than that calculated by the RR method.

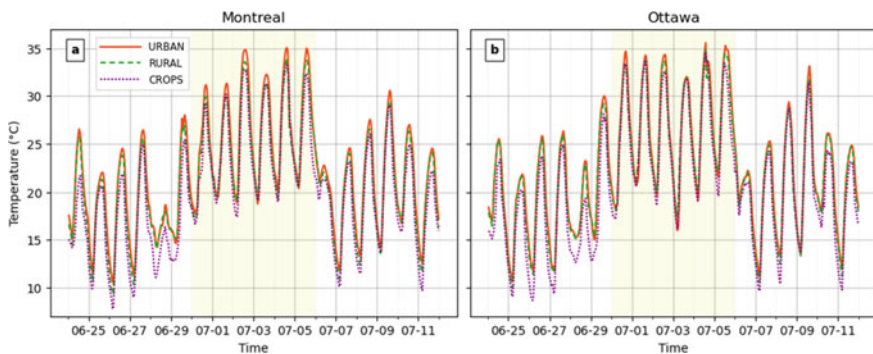


Fig. 322.3 Time series spatial-averaged air temperature profile before, during, and after the heatwave in **a** Montreal and **b** Ottawa. CROPS is the same area as URBAN, but the urban land type is replaced with croplands in the simulation

322.3.1 Air and Surface Temperatures

To examine the typical daily temperature patterns over the three (3) time frames (PRE, DUR and POS), the diurnal changes in the air temperature and land surface temperatures and the corresponding UHII values are shown in Fig. 322.4 and Fig. 322.5. The air temperature during the heatwave is always much higher than the temperatures over the other two-time frames (POS and PRE). The air temperature difference between DUR and POS can be around 7–8 °C in the afternoon. The air temperature after the heatwave is also higher than before the heatwave by around 2 °C. The results confirm that the time-averaged air temperature of CROPS is also always lower than that of URBAN, whereas the temperature of RURAL can be higher than URBAN during the morning, which is normally identified as the urban cool island (UCI) effect (Theeuwes et al. 2015; Yang et al. 2017). The air temperature UHII calculated by the UI method is, therefore, always higher than that calculated by the RR method. The use of the RR method shows that the UHII before and after the heatwave (PRE and POS) have a similar pattern whereas that during the heatwave can be quite different: for both cities, the UHII during a heatwave is even lower during the nighttime and in the morning, and it became higher in Montreal than that of the other two (2) time frames (PRE and POS) after 0800 LT. All three (3) time frames exhibit a similar diurnal pattern for the UHII calculated with the RR method, which peaks in the evening and drops to the minimum in the morning. On the other hand, this pattern is not maintained for the pre-heatwave period when calculated using the UI method. It has a much higher UHII than the other two (2) time frames (DUR and POS), and two peaks occur, one in the morning between 0800 and 1200 LT and one in the evening. In general, the heatwave does not necessarily enhance the air temperature UHII, especially in the nighttime and early morning before 0800 LT. And the UHII calculated using the UI method exhibits a much higher UHII before the heatwave even though its temperature is lower than the other two periods (DUR and POS).

The surface temperature between the different time frames showed a similar pattern in that the temperature difference between the URBAN and RURAL/CROPS areas amplifies during the daytime and the nighttime more closely align to each other, so the maximum surface temperature UHII always happens during the daytime. With the use of the RR method, the UHII of surface temperature is higher during the heatwave (DUR) than that in PRE and POS in the daytime from 0800 to 1700 LT in Ottawa and 2100 LT in Montreal. Whereas the UHII calculated by the UI method is also higher than the other two (2) time frames (DUR and POS) most of the time, which is similar to the UHII calculated using air temperature. As well, the UHII calculated by the UI method is also higher than that calculated with the RR method. The UCI is mainly noticed in Ottawa during and after the heatwave when calculating using the RR method, and it is also found from the result of the UI method for the period during the heatwave, which is quite different from the calculation with air temperature. This indicates that even though the two cities are close to each other and are located in a region with similar climate conditions, the UHI pattern can

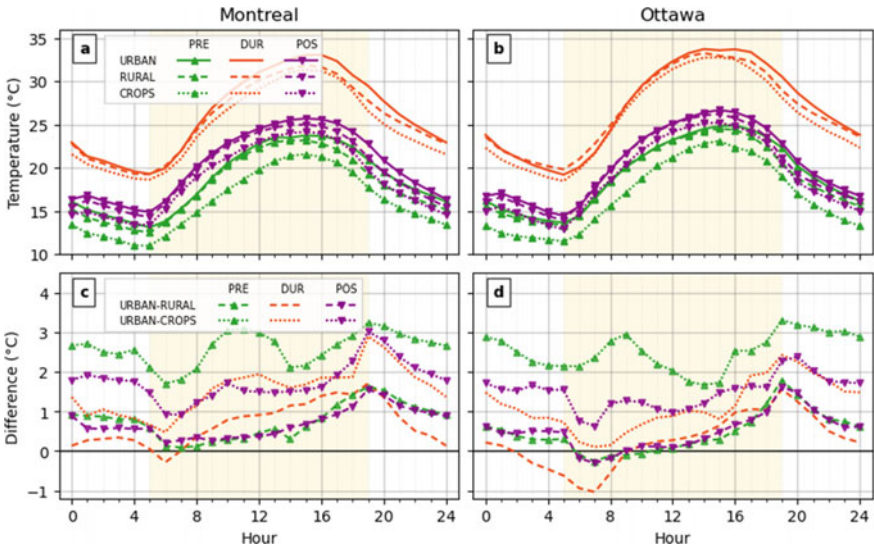


Fig. 322.4 Diurnal variation of the **a, b** air temperature and the **c, d** urban–rural difference in **a, c** Montreal and **b, d** Ottawa

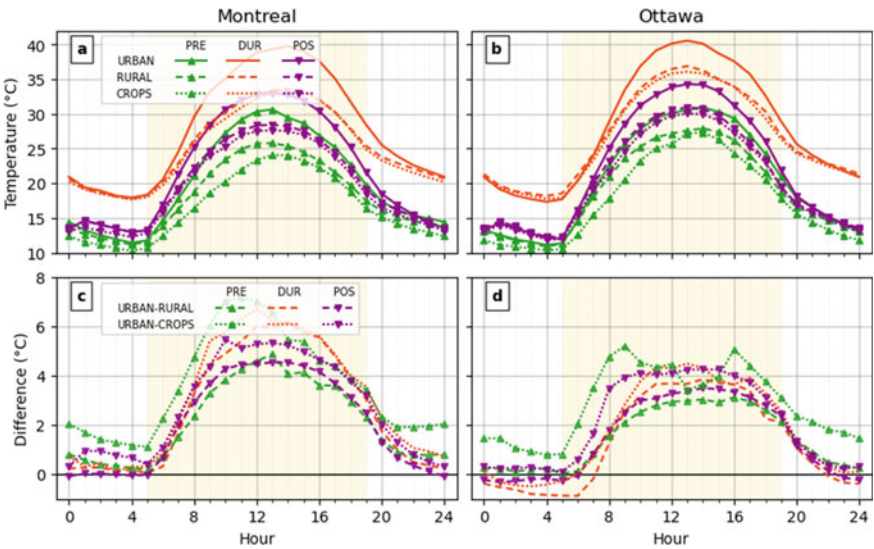


Fig. 322.5 Diurnal variation of the **a, b** surface temperature and the **c, d** urban–rural difference in **a, c** Montreal and **b, d** Ottawa

still be quite different, which can be highly related to the size of the cities, and the surrounding land use and land cover conditions.

322.3.2 Wind Speed and Wind Directions

The wind rose charts in Fig. 322.6 show the evolution of the wind direction in the period from before until after the heatwave. The wind direction gets increasingly dominated by the south-west wind for both cities, and the northwest wind is also non-negligible in the post-heatwave period (POS); this implies that the extreme heat event might be affected by the southwest wind and the wind from the northern side (higher latitude) may help cool the city areas, however, a more detailed analysis from a larger regional scale is needed to further investigate the impact of wind directions.

Figure 322.7 further shows the diurnal changes in the wind speed. The wind speed after the heatwave is much higher than that during and before the heatwave, indicating a stronger advection effect after the heatwave, which may help cool the city areas. The URBAN area has a much lower wind speed than the other two areas (RURAL and CROPS) for all three (3) time frames, which has limited convective cooling in the near-field area.

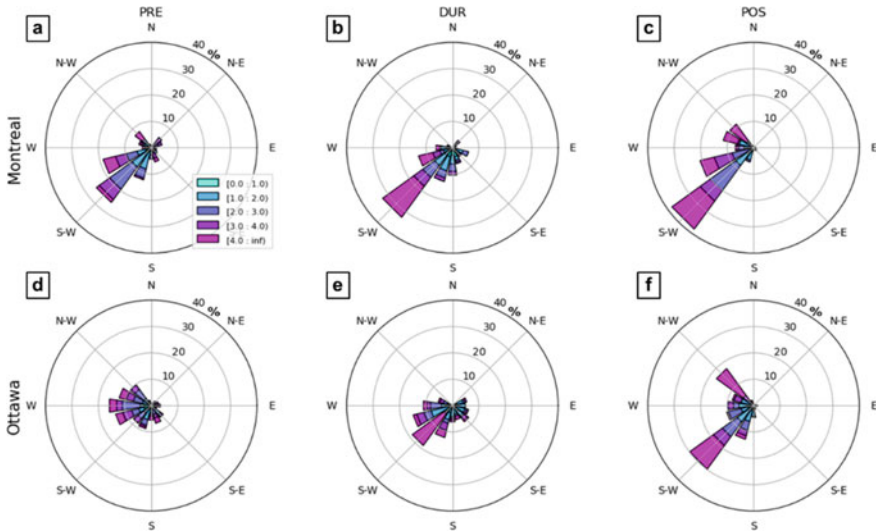


Fig. 322.6 Wind rose a, d before, b, e during, and c, f after heatwave for a, b, c Montreal and d, e, f Ottawa

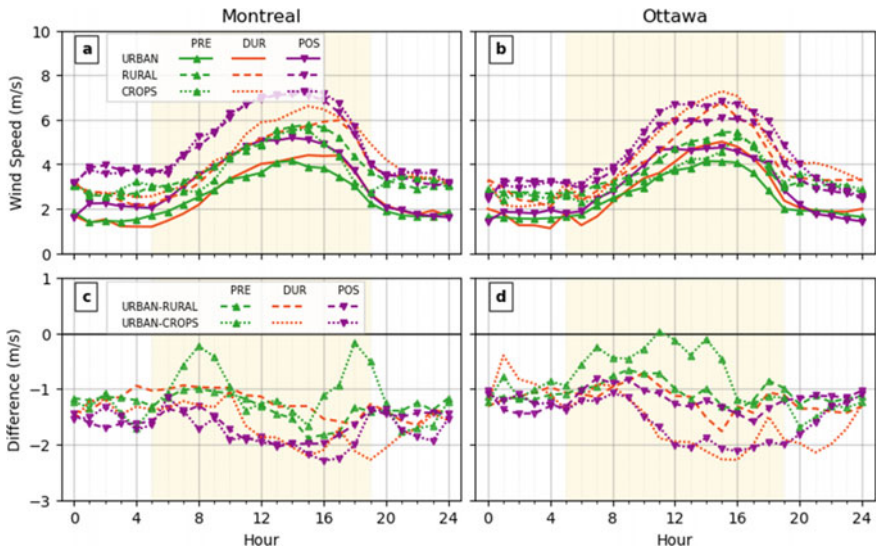


Fig. 322.7 Diurnal variation of the **a, b** wind speed and the **c, d** urban–rural difference in **a, c** Montreal and **b, d** Ottawa

322.3.3 Relative Humidity

Figure 322.8 shows the diurnal changes in the relative humidity (RH) in the three (3) time frames. In general, the URBAN areas are drier than the RURAL area, and RURAL is drier than the CROPS area, so the contrast in RH is more significant when calculated with the difference between URBAN and CROPS. This can be explained by the greater amount of moisture in the soil as is maintained by the natural land types in the CROPS area, which, therefore, provides more potential for evaporative cooling for the area.

322.4 Conclusions

The interaction between urban UHI and heatwaves is discussed in this study by comparing the variation of a few environmental variables such as air temperature, surface temperature, wind speed and wind direction, and the relative humidity across the three different time frames (PRE, DUR, POS). Two UHII calculation methods (UI and RR) are used, and their use is compared in the study. The results can be quite different when using the different methods, and the diurnal profiles of UHII can be quite different for air temperature and surface temperature. To further explain the physical roots behind the surface energy budget, soil moisture availability and the larger-scale atmospheric behaviour will be analysed in future work. The limitation

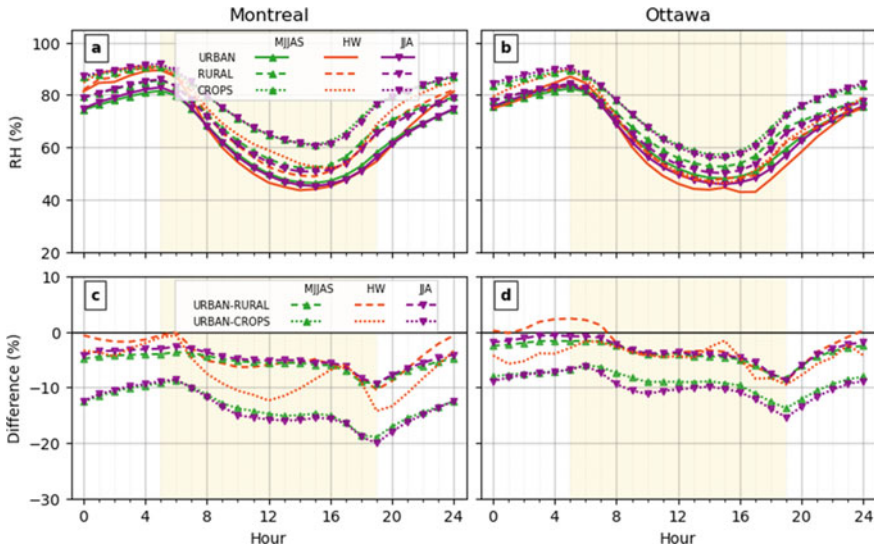


Fig. 322.8 Diurnal variation of the **a, b** relative humidity (RH) and the **c, d** urban–rural difference in **a, c** Montreal and **b, d** Ottawa

of the current study is that the short-term variations of UHI next to the heatwave were only considered. A comparison of the long-term UHI effects and the analysis of more heatwave events should be included in future studies.

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