Impact of Spatial Distributions of Climate Condition on Building Overheating

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Abstract. In this study, the spatial distribution of the urban climate is evaluated and its impact on indoor overheating conditions is assessed. This was done by modelling the near-field climate of Ottawa and Montreal at 1 km resolution for the summer of 2018 during which an extreme heat event occurred causing nearly 100 deaths in this area. The climate data obtained from Weather Research Forecasting simulations were used for assessing the extent of overheating within a prototype model of a single-detached home using EnergyPlus. The overheating conditions were evaluated using the mean temperature, the number of hours with the temperature above 28°C, and the number of hours cooling from a base temperature of 28°C. A workflow for selecting representative locations within the city for building overheating assessments was established by considering five (5) different quantiles, including 0%, 5%, 50%, 95%, and 100%, of the three calculated overheating metrics over the urban and the rural area. The degree of indoor overheating in homes was quantified and differences in overheating of homes in urban and rural settings as well as those arising within different urban areas (intra-urban) were determined. The most significant intra-urban indoor mean temperature differences of buildings at different locations were 1.8°C for Montreal and 1.6°C for Ottawa. For the number of hours with a temperature above 28°C, the intra-urban difference can be up to 829 hours for both cities. It was also found that the overheating conditions between different locations may be affected by the external air temperature and other variables, such as the local wind speed, which greatly varied the natural ventilation air change rate of buildings. The overheating conditions in buildings of different locations were also compared by analyzing the time-series variation in temperature. It was determined that there always exists a difference between the duration and intensity of indoor overheating in single-family homes of different locations.

Keywords. WRF, Overheating, Extreme heat event, Urban heat island, EnergyPlus
DOI: https://doi.org/10.34641/clima.2022.120.389

1. Introduction

As a consequence of global warming, the increased occurrence of extreme heat events leads to higher morbidity and mortality [1]. Overheating in buildings comes to be a major problem during the heatwaves which can impose fatal threats to the occupants' health [2]. The external climate is a significant driver of indoor building conditions. Taylor et al. [3] conducted multiple building simulations for six cities from different climate regions across the UK to justify the importance of the weather files in the assessment of building indoor overheating conditions. Amoako-Attah and B-Jahromi [4] examined the variation of the simulated indoor operative temperature of detached residential buildings in London by using different weather files, which also affirmed the importance of selecting weather files for building-related studies. Cumulative efforts have been invested in finding the most representative weather file from a long-term climate series for building simulations [5].

The traditional representative weather year data are normally selected from multiple years which cannot reflect the spatial variation of the climate conditions, while buildings may expose to very different overheating risks even in the same city due to the various surrounding conditions [6]. In 1999, a field monitoring campaign in London constructed a network of fixed temperature stations along eight transects of the city covering the whole urban and suburban areas, which provided the air temperature data to be strong evidence of the urban heat island phenomenon [7]. The monitored data have been adopted by Kolokotroni et al. [8] to develop the London Site-Specific Air Temperature (LSSAT) model using an artificial neural network (ANN), which provides the localized weather data for a series of studies to discuss the urban heat island effect on buildings [9]. These studies used the climate data at the measured location across the Greater London Area, and a clear trend can be found that with the increase of the distance from the urban center the indoor temperature and cooling energy can be lower [10] in summer while the heating energy consumption in winter can be higher [11]. These studies compare the overheating in buildings using the climate conditions at limited locations with measuring stations, which can be hard to reflect the overall pattern for the whole city.

This study adopted the weather files extracted from a fine-resolution regional climate model, which permits the urban effect on climate. Multiple locations over the cities are sampled for building simulation to perform an overheating assessment. The results of this study quantify the intra-urban difference and the urban-rural difference in terms of building overheating.

2. Method

2.1 study area, model and data

This study focus on the analysis of two Canadian cities: Ottawa and Montreal. The five months (May 01 - September 30) are evaluated for the whole summer of 2018, because it covers a heatwave event that happened in the two cities from June 30 – to July 05, 2018, which caused approximately 100 deaths in the area. The high-resolution climate dataset has been simulated using the Weather Research and Forecast model at a grid resolution of 1 km. For the detailed configuration of the climate models please refer to [12,13].

2.3 urban and rural areas

In this study, the urban area is identified by the urban grid dominated by the urban and built-up land cover types around the centre of the city. The rural areas are identified by a polygon buffer surrounding the boundary of the urban region [14]. This study considered a buffer distance of 10km from the urban boundary for the rural area to avoid introducing other uncertainties caused by different climate conditions of father geospatial regions, which is also consistent with the implementation in existing studies [15]. The regions within 3km distance to the urban boundary are excluded because they might still be highly affected by the urban region [14]. We also excluded the water bodies and the terrains 50m higher than the highest elevation of the urban area, which might have a significant impact on the local temperature for the urban heat island intensity calculation [14,16].

The distribution of the land cover types and the shapes of the urban boundary, rural boundary and the excluded buffer region in between is specified in **Fig. 1**. The urban area of Montreal city is covered by 1184 1km grids which is double times the urban areas of Ottawa that are covered by 501 grids. The number of grids for the rural area of Montreal and Ottawa is 1316 and 1112.

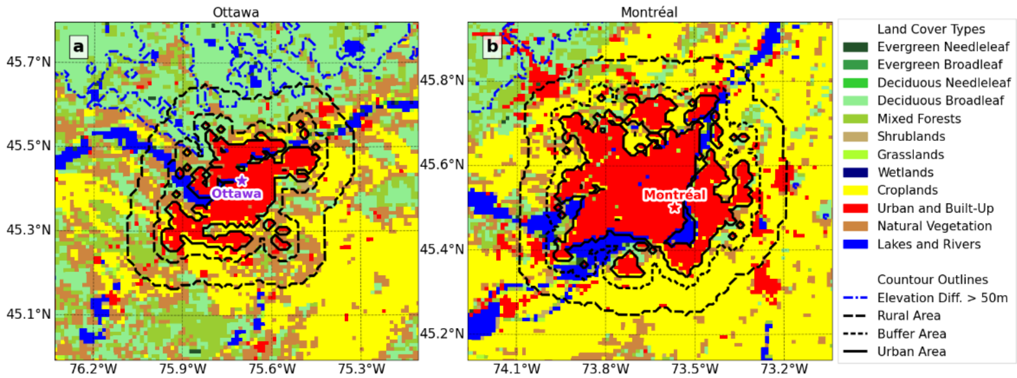

Fig. 1 - Land use and land cover with the outlines of urban and rural areas of a) Ottawa and b) Montreal cities

2.2 locations for building simulation

To specify the weather data to be used for the overheating assessment, multiple studies have been focused on developing a procedure for creating representative climate datasets from long-term climate datasets [17]. CIBSE [18] has developed a systematic approach to selecting the design summer year (DSY) by evaluations of several overheating metrics for the climate data from different years. A similar concept is adopted here in this study. Instead of selecting the climate data from multiple years, the evaluation of the climate data has been conducted over the different grids across the whole city to find the locations exposed to different levels of heat conditions.

For this study, the selection of the representative locations in the urban and rural areas adopted the temperature-based overheating assessment methods, which is the most straightforward for the comparisons of the indoor overheating conditions from different locations in the same city. The locations are selected by the evaluation of three different aspects, including a) the time-averaged air temperature over the evaluated five months, b) the overheating hours above the fixed temperature threshold, c) and the cooling degree hours (CDH) with the base temperature of the fixed temperature threshold. The fixed temperature threshold in this study is 28°C for both the outdoor and the indoor conditions since it is the most used value in the literature and standards for overheating assessment in residential buildings [19] and the selection of extreme weather files [18]. It is defined to be an extremely hot condition when the temperature is higher than 28°C, so the number of hours above 28°C reflects the occurrence of overheating within the evaluated period. The cooling degree hour is defined as the cumulative number of overheating hours weighted by the magnitude of exceedance above the threshold temperature values, which evaluates both the temperature levels and the occurrence of overheating, the equation to calculate it is:

$$CDH = \sum_{T_{air}>28} (T_{air} - 28) \qquad (1)$$

After the three metrics are calculated, the locations with the five (5) different quantiles, 0%, 5%, 50%, 95%, and 100%, of the three evaluated metrics are considered to represent the general conditions in the city. The quantiles of 0% and 100% are selected for the locations of the extreme cases with the maximum and minimum potential of overheating in the city, and the quantiles of 5%, 50% and 95% help to conclude the most possible range of the overheating conditions in the city. The selection of the five locations using each of the metrics is conducted separately for the urban and rural regions to show the general difference in the climate conditions between the urban and rural areas. Therefore, 10 locations would be selected using each of the metrics for each city, and it is expected to have 30 locations selected in total for each city with the 3 metrics considered.

In **Fig. 2**, the selected locations are summarized with the distribution of the three metrics. The selected locations are indexed by the metrics for the selection (T for mean temperature, H for overheating hours, C for cooling degree hours) followed by its level of percentile of the evaluated metric hereafter. For example, T100 indicates the location with the maximum value in the urban/rural area in the city, H00 for the location with the minimum overheating hours in the urban/rural area in the city, and C50 means the cooling degree hour of the location is the median value of the whole urban/rural area of the city.

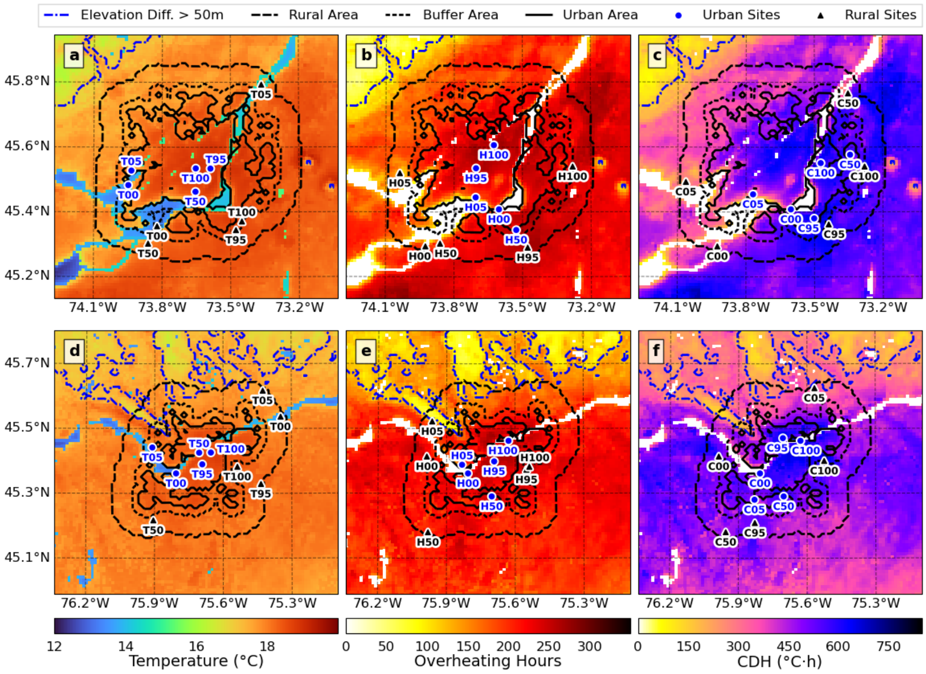

Fig. 2 - Site selection based on the three criteria of a, d) mean outdoor air temperature over the 5 months; b, e) the overheating hours above 28°C; and c, f) Cooling degree hours (CDH) with a base temperature of 28°C.

2.3 building model and overheating assessment method

To demonstrate the difference in indoor overheating at the different selected locations, a single-house archetype model is adopted for simulating the indoor thermal conditions in EnergyPlus. The configuration of the building model follows the National Building Code of Canada and National Energy Code of Canada for Buildings. To evaluate the overheating under a free-running condition, the building model in this study is naturally cross-ventilated using the Airflow Network Model in EnergyPlus. For a more detailed configuration of the building models please refer to [12]. The overheating of the buildings is identified by the number of hours with an indoor operative temperature above 28 °C which is consistent with the location selection criteria in section 2.2.

3. Results

3.1 comparison of indoor overheating at selected locations

The indoor overheating conditions of the bedrooms in the single house buildings at different locations in the WRF model are summarized in **Fig. 3**. The buildings in rural areas may have lower values in the overheating metrics than the urban area in general, this is due to the cooler outdoor air temperature and higher wind speed in the rural area. For the locations with the 50 quantiles in Montreal, the overheating hours at the three locations in the urban area have an average of 104 hours higher than that of the three locations in a rural area. For Ottawa, the difference in the overheating hours between urban and rural is even larger.

A distinct difference can also be found in **Fig. 3** between locations in the urban area. For Montreal, location H100 has the maximum overheating hour of 862 hours, and T00 has the minimum of 33 hours, which identified a possible overheating hour difference of 829. For Ottawa, the maximum evaluated overheating hour difference is also 829 hours which is observed between T100 and T00. Notably, there exists a significant difference between locations with 00 quantiles and 05 quantiles, while the difference between locations with quantile 05 and quantile 100 is much smaller than that. This reminds us that only a small portion of the locations (grids) may fall into the evaluated range between locations with 00 quantiles and 05 quantiles, while most of the locations (grids) should be in the range of that between locations with quantile 05 and quantile 100. Therefore, when conducting the overheating analysis of the buildings in the city, people should avoid selecting these cool locations which cannot represent the overall overheating in the city.

Fig. 3 also exhibited the trend that, no matter for urban or rural areas, locations selected with the higher quantile of the overheating metrics for outdoor climate may have correspondingly more severe overheating indoors. However, exceptions can still be found that locations with higher quantiles may have lower mean operative temperature or overheating hours. For example, in Montreal, the urban C100 has a lower mean operative temperature and overheating hours than those from T, H, C95, T50 still has higher overheating hours than the three locations with 05 quantiles, but it has a lower mean operative temperature than that at T05. A similar outcome also happens in the urban area of Ottawa, the location H, C100 has both the mean operative temperature and overheating hours even lower than the buildings at T, H, C50 and H05, and location H05 may have a higher mean operative temperature than H, C50 though its overheating hour is still smaller than H, C50. This can be explained by the difference in the local wind speed which may lead to the different natural ventilation conditions of the building. The average air change rate of the rooms over the 5 months is therefore provided in **Fig. 4**. It can be found that, for the locations in Montreal urban area, C100 and T50 have much higher air change rates than the other sites, which indicates the natural ventilation at these two locations helped with the indoor temperature control. Among the locations in Ottawa, the air change rate in the buildings at H, C100 is much higher than the other sites, this significantly reduced the overheating in the buildings, while for H05, the air change rate is much lower than other sites apart from climate T, H, C00, which explains, why it may have comparable or even more severe overheating than locations with quantile 50. This suggests the importance to include the local wind condition for the whole building thermal simulation of naturally ventilated buildings.

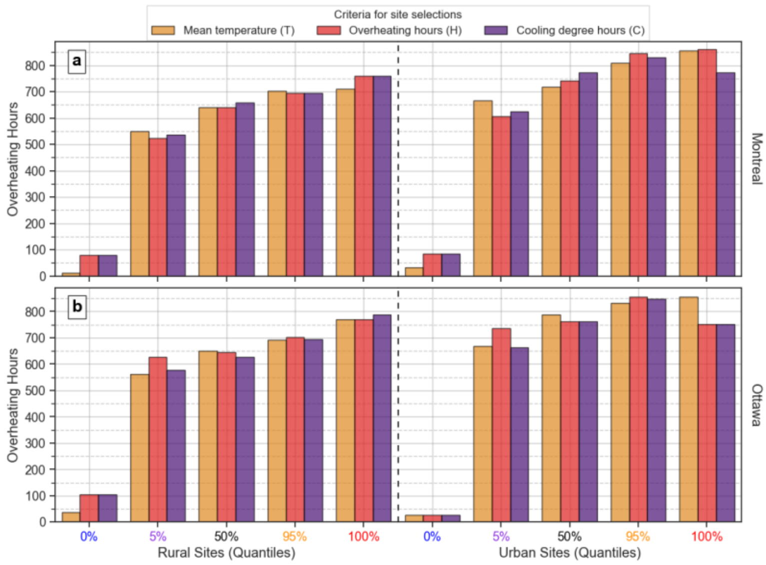

Fig. 3 - Comparison of the overheating hours above 28°C during the 5 months of summer (MJJAS) in the bedroom of single house buildings using the climate data from different selected locations in a) Montreal and b) Ottawa. (The colours of bars shown in the legend is to indicate the different criteria used for location selections)

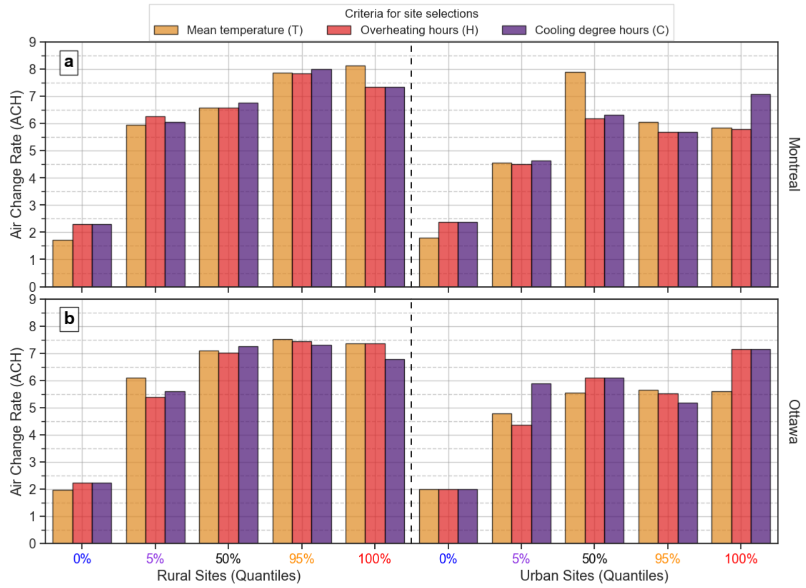

Fig. 4 - Comparison of the mean air change rate during the 5 months of summer (MJJAS) in the bedroom of single house buildings using the climate data from different selected locations in a) Montreal and b) Ottawa (The colours of bars shown in the legend is to indicate the different criteria used for location selections)

3.2 comparison of overheating in the urban area

The longer overheating exposure time can also impose a great threat to the health and safety of the occupants due to the cumulative water loss and the increased core temperature of the human body [20]. This requires a better estimate of the duration of the overheating, while the summarized overheating metrics of the overheating hours cannot fully reflect the detailed overheating information in the time series. The H95 and H05 locations in the urban area of Montreal are selected for the comparison of the whole time series between different locations. The hourly data of outdoor air temperature and the indoor operative temperature have been shown in the heatmap plot in **Fig. 5**. It clearly shows that the indoor operative temperature is higher than the outdoor air temperature in general, the temperatures indoors are elevated compared to that of the outdoors due to the indoor heat gain by the building utilities. For both the indoor and outdoor conditions, the simulation captured the higher temperature during the daytime than the nighttime and the more severe high temperature during the heatwave period than the rest of the days in the summer. The maximum indoor operative temperature at H95 during the heatwave can be 38.5°C, and 37.8°C at H05.

To better compare the difference in time series between the locations in the urban, the heatmap of the hourly temperature of H95 subtracted by that of H05 in Montreal is plotted in **Fig. 6** as an example. A greater temperature difference between the sites happens outdoors than indoor locations, while they still exist a great temperature difference indoors. The indoor operative temperature at H95 is higher than that at H05 for 75% of the hours during the five months, and the difference can be even higher in the hot hours during the heatwave period, which can be as great as 5.8°C. The indoor condition at both locations exhibits a longer time to be higher than 28°C compared to the outdoors, and the overheating conditions at H95 may normally have one or two hours longer on each of the days than that at H05, no matter for indoors or outdoors. In general, the increased overheating hours at a hotter location are normally distributed next to the existing overheating hours that can be found from a cooler location in the same city, this helps to better quantify the increased mortality risk at a location compared to another one in the city. And there are also exist several days that may have several hours of overheating above 28°C found in the building at H95, while none of such overheating can be observed in the building at H05. For example, there are 9 overheating hours at H95 on August 7, while no overheating hour is outlined at H05. A higher possibility is also observed for the building at H95 to have the condition of temperature above 28°C extends after 23:00, while for location H05, this overheating condition normally ends before 23:00. This means using the climate data at a cool location in the city, e.g., H05 may significantly underestimate the overheating during the night.

3.3 comparison between urban and rural locations

The overall difference in overheating conditions between urban and rural areas has been shown in **Fig. 3**. To better show the difference between locations in the urban and rural areas along with the time series, the locations with 50 percentiles (median) of the overheating metric are compared between urban and rural areas. For example, the urban T50 of Ottawa and rural T50 of Ottawa has been compared and their difference has been plotted in **Fig. 7**. Although the location from the urban area has a higher mean temperature than the rural location as observed, a distinct lower temperature can still be observed in the morning than the location from the rural area for the outdoor condition. It can be identified as the urban cool island, which is consistent with existing findings [21]. While for the comparison of the indoor operative temperature, the building in an urban area does not show that many hours lower than those in a rural area, and the hours with the lower indoor operative temperature in an urban area would occur later than the cool hours in the outdoor.

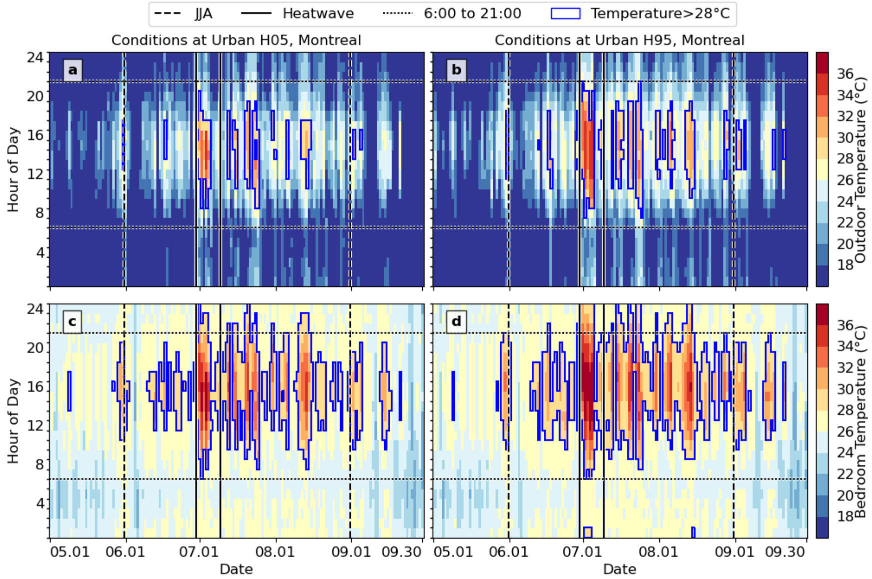

Fig. 5 - Time series heatmap of the a, b) outdoor air temperature, c, d) bedroom operative temperature at a, c, e) H05, and b, d, f) H95 locations in Montreal.

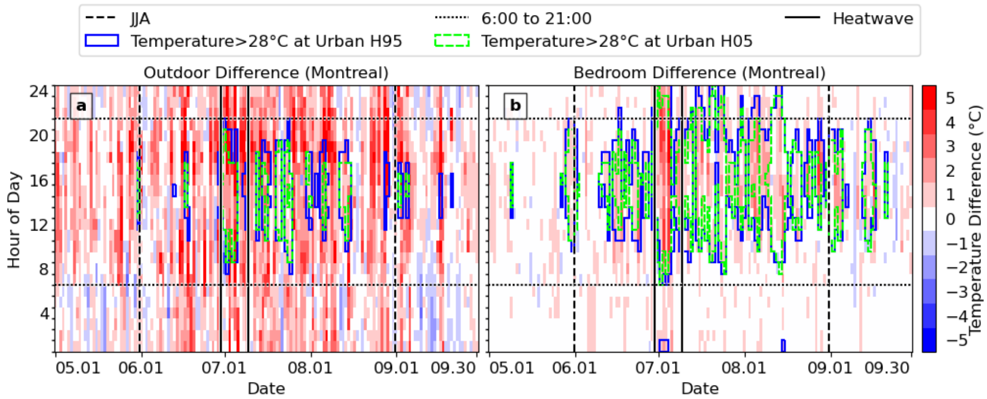

Fig. 6 – The difference of temperature at two urban locations, H95 and H05, of Montreal for a) outdoor air temperature and b) operative temperature in bedrooms

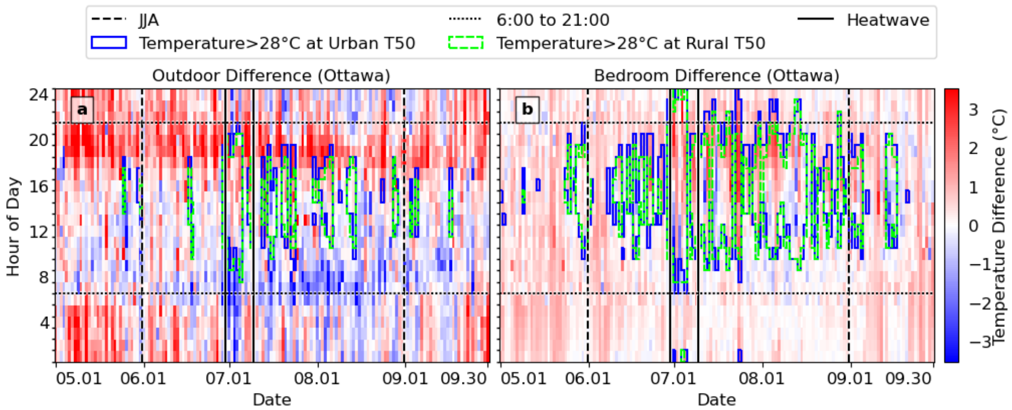

Fig. 7 - The difference of temperature between the T50 locations in urban and rural locations of Ottawa for a) outdoor air temperature and b) operative temperature in bedrooms

The absolute value of the temperature difference is also much smaller than that for the outdoor condition comparisons. For the example in **Fig. 7**, the building in the urban area has been exposed to the outdoor temperature with 40% of the hours lower than that in the rural area, and the greatest difference can be -7.2°C found during the heatwave, while for the indoor condition, the building in the urban area has 22% of the hours lower than that in the rural area, and the greatest difference can be -4.5°C. This exhibits that the urban cool island in the buildings is normally postponed for each of the days and with attenuated intensity due to the higher thermal capacity and the internal heat gain in the building enclosures, and the indoor overheating in an urban area is more severe than that in a rural area.

4. Conclusions

This study has been devoted to quantifying the effect of the spatial distribution of climate data at different locations for the building thermal analysis. A complete procedure of evaluating the overheating conditions of different locations in the city from the high-resolution climate data has been demonstrated by evaluating the distribution of the overheating metrics across the whole city followed by selecting the locations with different quantiles of the overheating metrics. The indoor simulation results of using the different climate data from different locations in the high-resolution are compared together with their local outdoor climate conditions to show the importance of using the climate data at a proper location even for the same city. Conclusions can be summarized in the following points:

- Great intra-urban overheating condition difference has been detected through a comparison of the locations with overheating metrics of the quantile of 00 and 100. The difference in the overheating hours between the locations can be 829 hours in both cities.

- In general, overheating is more severe in an urban area than in a rural area, although an urban cool island effect can be found in the morning when comparing the weather conditions between urban and rural.

- The duration of the overheating may normally have 2 hours difference between locations with overheating metrics of 95 and 05 quantiles. And even for different locations with similar mean indoor operative temperature and overheating hour values, the period of overheating occurrence can be quite different.

- Locations with higher temperature-based overheating metrics may have a more severe overheating condition in the buildings in general, while other climate variables may also affect indoor overheating conditions. In this study, the local wind speed is found very important for the overheating evaluation of the buildings with operable windows for natural ventilation in which the wind speed can markedly change the indoor overheating condition by variating the overall air change rate of the building.

The current study used an archetype single-house building model for the demonstration, which is the limitation of the current study, and in the future, the similar simulation can be performed for other building types to generalize the conclusions from this study.

5. Acknowledgement

The research described in this paper was supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada through the Advancing Climate Change Science in Canada Program [#ACCPJ 535986–18] as well as funding from Infrastructure Canada by the means of Climate Resilient Buildings and Core Public Infrastructure project. This research was also made possible, in part, by Calcul Québec (www.calculquebec.ca) and Compute Canada (www.computecanada.ca).

6. References

[1] World Meteorological Organization (WMO), World Health Organization (WHO), Heatwaves and Health: Guidance on Warning-System Development, 2015.

[2] CIBSE, The limits of thermal comfort : avoiding overheating in European buildings, 2013. https://doi.org/10.1017/CBO97811074153 24.004.

[3] J. Taylor, M. Davies, A. Mavrogianni, Z. Chalabi, P. Biddulph, E. Oikonomou, P. Das, B. Jones, The relative importance of input weather data for indoor overheating risk assessment in dwellings, Building and Environment. 76 (2014) 81–91. https://doi.org/10.1016/j.buildenv.2014.03 .010.

[4] J. Amoako-Attah, A. B-Jahromi, The impact of different weather files on London detached residential building performance-deterministic, uncertainty, and sensitivity analysis on CIBSE TM48 and CIBSE TM49 future weather variables using CIBSE TM52 as overheating criteria, Sustainability (Switzerland). 8 (2016). https://doi.org/10.3390/su8111194.

[5] L. Guan, Preparation of future weather data to study the impact of climate change on buildings, Building and Environment. 44 (2009) 793–800. https://doi.org/10.1016/j.buildenv.2008.05 .021.

[6] C.K. Uejio, O. V Wilhelmi, J.S. Golden, D.M.

Mills, S.P. Gulino, J.P. Samenow, Intra-urban societal vulnerability to extreme heat: The role of heat exposure and the built environment, socioeconomics, and neighborhood stability, Health and Place. 17 (2011) 498–507. https://doi.org/10.1016/j.healthplace.2010.12.005.

[7] M. Kolokotroni, I. Giannitsaris, R. Watkins, The effect of the London urban heat island on building summer cooling demand and night ventilation strategies, Solar Energy. 80 (2006) 383–392. https://doi.org/10.1016/j.solener.2005.03.010.

[8] M. Kolokotroni, Y. Zhang, R. Giridharan, Heating and cooling degree day prediction within the London urban heat island area, Building Services Engineering Research and Technology. 30 (2009) 183–202. https://doi.org/10.1177/0143624409104733.

[9] E. Oikonomou, M. Davies, A. Mavrogianni, P. Biddulph, P. Wilkinson, M. Kolokotroni, Modelling the relative importance of the urban heat island and the thermal quality of dwellings for overheating in London, Building and Environment. 57 (2012) 223–238. https://doi.org/10.1016/j.buildenv.2012.04.002.

[10] M. Kolokotroni, X. Ren, M. Davies, A. Mavrogianni, London's urban heat island: Impact on current and future energy consumption in office buildings, Energy and Buildings. 47 (2012) 302–311. https://doi.org/10.1016/j.enbuild.2011.12.019.

[11] M. Kolokotroni, M. Davies, B. Croxford, S. Bhuiyan, A. Mavrogianni, A validated methodology for the prediction of heating and cooling energy demand for buildings within the Urban Heat Island: Case-study of London, Solar Energy. 84 (2010) 2246–2255. https://doi.org/10.1016/j.solener.2010.08.002.

[12] C. Shu, A. Gaur, L. (Leon) Wang, M. Bartko, A. Laouadi, L. Ji, M. Lacasse, Added value of convection permitting climate modelling in urban overheating assessments, Building and Environment. 207 (2022) 108415. https://doi.org/10.1016/j.buildenv.2021.108415.

[13] A. Gaur, M. Lacasse, M. Armstrong, H. Lu, C. Shu, A. Fields, F.S. Palou, Y. Zhang, Effects of using different urban parametrization schemes and land-cover datasets on the accuracy of WRF model over the City of Ottawa, Urban Climate. 35 (2021) 100737. https://doi.org/10.1016/j.uclim.2020.100737.

[14] H. Li, Y. Zhou, X. Wang, X. Zhou, H. Zhang, S. Sodoudi, Quantifying urban heat island intensity and its physical mechanism using WRF/UCM, Science of the Total Environment. 650 (2019) 3110–3119. https://doi.org/10.1016/j.scitotenv.2018.10.025.

[15] K.B. Moffett, Y. Makido, V. Shandas, Urban-rural surface temperature deviation and intra-urban variations contained by an urban growth boundary, Remote Sensing. 11 (2019). https://doi.org/10.3390/rs11222683.

[16] D. Zhou, S. Zhao, S. Liu, L. Zhang, C. Zhu, Surface urban heat island in China's 32 major cities: Spatial patterns and drivers, Remote Sensing of Environment. 152 (2014) 51–61. https://doi.org/10.1016/j.rse.2014.05.017.

[17] A. Laouadi, A. Gaur, M.A. Lacasse, M. Bartko, M. Armstrong, Development of reference summer weather years for analysis of overheating risk in buildings, Journal of Building Performance Simulation. 13 (2020) 301–319. https://doi.org/10.1080/19401493.2020.1727954.

[18] CIBSE, Design Summer Years for London, Technical Memoranda 49. (2014) 1–29.

[19] CIBSE, Environmental design CIBSE: Guide A, 2011.

[20] A. Laouadi, M. Bartko, M.A. Lacasse, A new methodology of evaluation of overheating in buildings, Energy and Buildings. 226 (2020) 110360. https://doi.org/10.1016/j.enbuild.2020.110360.

[21] S. Duan, Z. Luo, X. Yang, Y. Li, The impact of building operations on urban heat/cool islands under urban densification: A comparison between naturally-ventilated and air-conditioned buildings, Applied Energy. 235 (2019) 129–138. https://doi.org/10.1016/j.apenergy.2018.10.108.