Importance of Microscale Climate Simulations in City Scale Overheating Assessments

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Abstract. This study demonstrates the importance of high-resolution climate simulations when conducting city-scale outdoor heat wave alert and indoor overheating assessments. This is done by modelling urban climate of the Ottawa and Montreal cities at 1 km and 25 km, typical for regional climate modelling respectively, over the summer of 2018 when an extreme heat event caused around 100 deaths in these cities. It is shown that urban climate characteristics (higher temperatures, lower wind speeds, lower relative humidity in the urban core than surroundings) are better simulated at 1 km than at 25 km spatial resolution. Indoor conditions are simulated for an archetype model of a single detached house using EnergyPlus software for two locations within the cities: a) city center and b) airport location. It is shown that the simulated indoor air temperature in the building is highly correlated with the outdoor air temperature. Furthermore, it is found that the maximum indoor air temperature difference of the city center and the airport can be as high as 8°C in Montreal and 9°C in Ottawa. Such intra-urban differences in overheating in buildings will be ignored if microscale simulations are not performed, highlighting their importance for building overheating assessments in cities.

1. Introduction
Overheating in buildings can impose a major threat to its occupants' health [1]. The external climate is a significant driver of indoor building conditions. Taylor et al. [2] conducted multiple building simulations for six (6) 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 et al. [3] also 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 to incorporate the urban heat island effect into weather files for building related studies. Demanuele et al. [4] analyzed the measured air temperature from 20 temperature measurement sites across the East-West transect of the Greater London Area to evaluate the significance of urban heat island effect on building energy use and indoor thermal comfort, and they suggested to use localized weather files to assess overheating within London area. The study by Pyrgou et al. [5] statistically compared the data collected from two different urban weather stations with the Typical Meteorological Year (TMY) and Test Reference Year (TRY) data, highlighted the importance of the need to frequently update the building simulation weather files to include the microclimate phenomena to consider the urban heat island effect and extreme conditions.
To discuss the effect of the spatial resolution of climate data on building simulation, Eames et al. [7] have compared the building simulation with the 5km × 5km gridded climate dataset and the simulated/resampled 25km × 25km dataset. The 5km × 5km gridded climate dataset in their study was created Perry [6], which was interpolated from a network of multiple weather stations. Chowienczyket al. [8] also explored the effect of urban heat island in a similar way by analyzing the measured data from the UK Meteorological Office observing network. Taylor et al. [9] established a new workflow of mapping the indoor overheating risks over the Sherfield city with seventeen (17) 5km×5km grid in the database of 2009 UK climate projections (UKCP09).

Most of the past studies assessing the importance of local climate on building thermal environment simulations have been based on the observational data recorded at a limited number of measurement sites or model data simulated at a coarse resolution. In this study, a Weather Research and Forecasting (WRF) model [10], is used to generate the high-resolution urban climate data at 1 km spatial resolution. The necessity of using such high-resolution urban climate data for building-related studies is discussed by comparing the high-resolution WRF results with a lower resolution of 25 km, which is the typical spatial resolution considered in RCMs.

2. Methodology

2.1. WRF simulation

![Figure 1. Computational domains of the 3 two-way nested domain for 1 km resolution simulation and the non-nested 25 km resolution simulation.](image)

In this study, climate conditions of the Ottawa-Montreal region in Canada were simulated using the WRF [10] model for three (3) months in the summer, June, July, and August of 2018, when an extreme heat event occurred from June 30 to July 6, 2018, with around 100 heat-related deaths in the region [11]. The National Centers for Environmental Prediction (NCEP) North American Regional Reanalysis (NARR) product (number ds608.0) were used as the initial and boundary conditions for the WRF simulations. The computational domain of the WRF simulation is plotted in Figure 1. For the high-resolution simulation, the innermost (third) domain is centered at the middle of Ottawa and Montreal, and the numerical domain contains three two-way nested domains with 276 × 296, 250 × 283, and 391 × 364 grid points, at a distance of 9, 3, and 1 km, respectively. For the lower resolution simulation, only
one non-nested domain was used, also centered in the middle of the two cities with 100 × 100 grid points and a grid size of 25 km. The domain covers a similar area with the utmost domain in the 1km resolution simulations. The detailed configuration of the WRF model is summarized in Table 1.

| Category                  | Physical parameterization scheme                                      |
|---------------------------|-----------------------------------------------------------------------|
| Microphysics              | WRF Single-Moment 3-class scheme (WSM3) [12]                          |
| Land surface model        | NOAH [13]                                                             |
| Planetary boundary layer  | Two-order closure Mellor-Yamada-Janjic [14]                          |
| Shortwave radiation       | Dudhia scheme [15]                                                    |
| Longwave radiation        | Rapid Radiative Transfer Model (RRTM) [16]                           |
| Cumulus parameterization  | Kain-Fritsch scheme [17]                                              |
| Advection scheme          | Runge-Kutta 3rd order                                                 |
| Land cover scheme         | MODIS 21-category                                                     |
| Number of vertical layers | 40                                                                    |
| Urban canopy model        | Multilayer UCM building effect parametrization (BEP) [18]            |

2.2. Building simulations

After the WRF simulations, the near-field climate data was extracted and used to perform building simulations in EnergyPlus [19]. A single detached house archetype building model was used in this study (Figure 2), with four (4) thermal zones: the underground basement, living room on the first floor, bedroom on the second floor, and an attic on the top of the building. The total footprint area of the building is 80.20 m².

| Table 2. Configuration of the building envelope of the single house. |
|---------------------------------------------------------------------|
| Component | Material and properties                               |
|----------|-------------------------------------------------------|
| Window   | Double clear with Low-E (U = 1.58; VT = 73%; SHGC = 0.67, WWR =15%) |
| Roof     | Asphalt shingles with attic insulation (R8.2)         |
| Walls    | Wood stud with Vinyl cladding (R4.5)                  |
| Basement Wall | Insulated concrete (R1.7)                             |
| Basement Slab | Insulated concrete (R1.6)                            |
| Blinds   | Internal blind                                       |

In Table 2, the building envelope configurations are listed, which follows the current (2015) construction practice for homes. The internal heat gains and schedules follow the descriptions from the National Building Code of Canada [20], with 5 W/m² for lighting, 5 W/m² for equipment, and 500 W/person for service hot water. The occupancy of the building was considered for a typical family of three people. For the building infiltration rate, an air change rate of 2.32 air changes per hour at 50 Pa
was considered for the current constructions obtained from a measurement database for the new homes of the region.

3. Results and discussions

3.1. Comparison of different resolution WRF results

The benefit of the climate data from the regional climate simulation is that a spatial and temporally complete set of climate variables is obtained compared to observational data recorded at a limited number of weather gauging sites. The distributions of the time-averaged air temperature from both the 1 km resolution and 25 km resolution simulations are shown in Figure 3. The black lines in Figure 3 specify the rivers and lakes, and the blue lines mark the constructed and built-up urban areas. The 1 km simulation is capable of providing more details compared to the 25 km resolution results. For example, the 1 km resolution result shows that the mean air temperature above or near the water bodies is much lower than the area with lands, while in the 25 km resolution case, the cooling effect of the water space cannot be resolved over the 25 km² grid area. Meanwhile, Montreal's urban area is mostly covered by only four (4) grid cells in the 25 km results and only one (1) grid cell for the city of Ottawa. Even though the coarse resolution simulation shows a higher air temperature over the urban area, much smaller variation of the mean temperature can be captured by the 25 km resolution simulation. For example, the maximum time-averaged temperature around both city areas can be more than 22 °C, but in the 25 km resolution results, the maximum value for Montreal is only around 20-21 °C and around 19-20°C for Ottawa. Therefore, it seems the low-resolution results smoothed out temperature extremes, which could be misleading for evaluating extreme heat conditions.

![Figure 3](image.png)

**Figure 3.** Time-averaged air temperature distribution across Montreal and Ottawa from the simulation of 1 km resolution and 25 km resolution.
3.2. Comparison of building simulations

As marked in Figure 3, the city center and the airport locations were selected to demonstrate how the climate data extracted from different locations in the city may yield different building overheating results. First, the difference in climate conditions between the two locations was compared to estimate their effect on building simulations. Four (4) climate variables, air temperature, global horizontal irradiation (GHI), wind speed, and relative humidity, were compared between the city centre and airport locations as shown by the histograms in Figure 4. The height of the bars shows the number of hours falls in the variable difference interval. It shows that the air temperature difference between the city centre and airport location \( (T_{city} - T_{airport}) \) for both cities has a higher possibility to be positive than negative, and the mean temperature difference in Montreal is 0.861 °C, and 0.185 °C in Ottawa. For the solar radiation, the difference between the city centre and the airport location is not that obvious: the mean difference values are close to 0, and the number of hours with positive values is similar to those with negative values. The city center's wind speed is lower than that of the airport location due to the damping effects from higher buildings and construction density of the city centre. The relative humidity of city centre is lower than the airport location, which is also reasonable because of the higher urban temperatures and impervious constructed surface area in the city centre suppresses the evaporative effect and other moisture transfer related effects. In general, the climate condition in the city centre may have higher air temperature and lower wind speed, which may lead to higher indoor air temperature. Although the lower relative humidity in the city centre might be beneficial in terms of thermal comfort, air temperature is still the primary driver to the heat stress of the human body.

To evaluate how the local climate may affect building simulations, the WRF climate condition at the two urban locations were used for building simulations. For the single house building investigated in this study, the major areas of interest are the bedroom and the living room. Therefore, the daily mean temperatures of these two thermal zones are plotted together with the outdoor daily mean air temperature in Figure 5. It shows that the indoor air temperature is much higher than the outdoor temperature, and the temperature in the bedroom is slightly higher than in the living room. The maximum temperature of the bedroom in Montreal can be around 55°C, while the maximum temperature of the living room in Montreal is around 52°C. The simulation in Ottawa exhibits a similar condition. The higher temperature in the bedroom room are due to temperature stratification resulting from inactive natural ventilation (windows are assumed closed). The time series plots also show that for Montreal, the daily mean air temperature and the daily maximum and minimum air temperature at the city centre are higher than
those at the airport location for most of the dates. For Ottawa, it shows that the buildings’ indoor temperature at the city centre is close to that at the airport location.

![Figure 5. Time series plot of the indoor and outdoor daily average air temperature (shading shows the range of temperature from minimum to maximum).](image)

To clearly show how the temperature difference between the sites may vary, the mean air temperature difference of the outdoor, bedroom, and living room spaces are summarized in Table 3. The air temperature difference in Montreal is much higher than in Ottawa, with an indoor temperature of around 1 °C higher at the city centre than the airport location.

**Table 3. Mean value of air temperature differences of Montreal and Ottawa.**

| City    | Outdoor Temp. Difference (°C) | Bedroom Temp. Difference (°C) | Living Room Temp. Difference (°C) |
|---------|------------------------------|-------------------------------|-----------------------------------|
| Montreal | 0.861                        | 0.982                         | 0.934                             |
| Ottawa  | 0.185                        | 0.258                         | 0.240                             |

The regression analysis in Figure 6 shows the outdoor air temperature difference at the two sites on the x-axis and the indoor air temperature difference between the two sites on the y-axis. The air temperature differences in the bedroom and living room are quite consistent while very different from the outdoor situation. The scatters in the plot show that the maximum indoor air temperature difference can be as high as 8 °C in Montreal and 9 °C in Ottawa (it is important to show the time for this difference). In general, the range of variation along the difference of indoor temperature (from -5 to 8 for Montreal, and -7 to 9 for Ottawa) can be greater than the outdoor temperature difference (from -3 to 8 for Montreal, and -6 to 4 for Ottawa). A positive correlation can be observed between the temperature
difference values between the indoor and outdoor, which means that the higher the outdoor air temperature difference, the greater the indoor air temperature.

![Comparison of indoor and outdoor air temperature difference between city centre and airport](image)

**Figure 6.** Comparison of the indoor and outdoor air temperature difference between the city centre and the airport.

4. **Conclusions**

This study demonstrates the importance of conducting microscale urban climate simulations when conducting building overheating assessments. Major conclusions from the study are:

a) The microscale simulations better capture urban climate characteristics than lower spatial resolution simulations.

b) The indoor air temperature is positively correlated with the outdoor temperature in the city.

c) The maximum indoor air temperature difference between the city center and the airport locations can be as high as 8 °C in Montreal and 9 °C in Ottawa highlighting the need for conducting microscale urban climate simulations to take these intra-urban differences in climate into consideration for overheating assessments.

The study would be continued by selecting more representative locations in the city to examine the changes in indoor conditions between different sites instead of the two locations considered in the current study. In addition, climate data generated from WRF simulations at different resolutions needs to be used for building simulations to further assess the sensitivity of simulated indoor overheating impacts on the resolution of climate simulations.

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