Analysis of multiple building overheating assessment metrics for long-term indoor thermal patterns in 12 Canadian cities

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Abstract
Climate change is a major contributor to extreme heat events, which have been a threat to the health of building occupants. It has been found that the rates of mortality and morbidity are much higher for urban dwellers during prolonged periods of elevated outdoor temperature. However, only limited studies have been conducted on the current overheating problems in buildings of different Canadian cities. This study considered multiple existing building overheating metrics, and the trend of evolution of indoor thermal conditions has been analyzed through linear regression. To permit analyzing the long-term variation of indoor conditions within typical buildings located in different cities across Canada, a series of building simulations were performed using weather station data over a historical period ranging from 1986 to 2016. Twelve (12) cities across Canada were selected for analysis that was located in different climate zones. This study determined the current overheating conditions under the 31-year historical climate conditions in two (2) building types: schools and offices.

Key Innovations
- Evaluate the overheating condition in cold climate regions in Canada
- Compare the difference of the overheating pattern in 12 cities.
- Evaluate the variation of overheating in the past 31 years.

Practical Implications
Few studies have been conducted on the overheating conditions in cold climate regions. In this study, the current overheating conditions are evaluated in typical buildings of 12 major cities in Canada. The building simulations employed 31 years of historical data from observed weather data to capture summertime overheating conditions in Canada.

Introduction
Building overheating-related studies have been ever increasing over the past 10 years, and around 40% of these studies have been contributions from the UK, which is a temperate climate (Chen 2019). The occurrence of overheating events with mortality and morbidity have been more frequent in recent years (Lamothe et al. 2019). People from cold or temperate climates, such as that of Canada, maybe more vulnerable than those residing in other climates because they may be less acclimatized to warm temperatures and levels of humidity occurring during extreme heat events, and as well, they may have limited access to air conditioning (Armstrong et al. 2010). To the authors' best knowledge, there are still few discussions of the current status of overheating in cold climates, particularly in Canada.

In this paper, existing methods for assessing overheating in buildings have been collected based on examining public literature, standards, and codes. After that, these methods are compared using building simulations undertaken over 31 years, the results of which permit discussing the strengths and weaknesses of these methods for different Canadian cities in this study. A combination of the assessment methods was selected to provide a comprehensive description of the heat events as occur in buildings. The method was then applied to evaluate the annual changes in 12 Canadian cities of overheating in two (2) types of buildings, including schools and offices, subjected to historical climate data obtained from multiple weather stations of Environmental and Climate Change Canada (ECCC), and as well, long-term climate loads as may arise in the future. This study provides an answer to how changes in outdoor weather conditions may affect indoor building conditions for the long-term duration of 31 historical years.

Methods

<table>
<thead>
<tr>
<th>City name</th>
<th>Short name</th>
<th>ASHARE zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calgary</td>
<td>CAL</td>
<td>7</td>
</tr>
<tr>
<td>Charlottetown</td>
<td>CHA</td>
<td>6A</td>
</tr>
<tr>
<td>Halifax</td>
<td>HAL</td>
<td>6A</td>
</tr>
<tr>
<td>Moncton</td>
<td>MNC</td>
<td>6A</td>
</tr>
<tr>
<td>Montreal</td>
<td>MON</td>
<td>6A</td>
</tr>
<tr>
<td>Ottawa</td>
<td>OTT</td>
<td>6A</td>
</tr>
<tr>
<td>Saskatoon</td>
<td>SAS</td>
<td>7</td>
</tr>
<tr>
<td>St. Johns</td>
<td>STJ</td>
<td>6A</td>
</tr>
<tr>
<td>Toronto</td>
<td>TNT</td>
<td>5A</td>
</tr>
<tr>
<td>Vancouver</td>
<td>VAN</td>
<td>4C</td>
</tr>
<tr>
<td>Winnipeg</td>
<td>WIN</td>
<td>7</td>
</tr>
<tr>
<td>Whitehorse</td>
<td>WHH</td>
<td>7</td>
</tr>
</tbody>
</table>

In this study, 12 Canadian cities of different climate zones were selected to investigate building indoor overheating conditions. The distribution of the 12 cities is plotted on the map in Figure 1. The ASHRAE climate zones...
(ANSI/ASHRAE 2013) of the cities are shown in different colors for each of the four (4) climate zones:

- **4C**: Mixed – Marine
- **5A**: Cool – Humid
- **6A**: Cold – Humid
- **7**: Very Cold

The northernmost city selected in this study was Whitehorse, which is in climate zone 7 of very cold climate. The southernmost city is Toronto, in climate zone 5A. The 12 cities are selected to cover different climate zones in Canada, which can, therefore, represent the current overheating conditions in Canada.

Figure 1 Distribution of selected Canadian cities and their climate zones.

Figure 2 Boxplot of a) air temperature; b) relative humidity; c) global horizontal radiation; d) wind speed in the 12 cities.
Climate data

The climate data are based on historical observations from multiple climate gauging stations within the selected cities from Environment and Climate Change Canada (ECCC). The long-term time-series climate data over the 31 years (1986-2016) was processed and generated following the method given by (Gaur et al. 2019); the climate data from the weather station with the most data available is first selected for the construction of the long-term climate dataset; then for the missing data of small gaps, the time series is fixed by linear interpolation of the most adjacent data points; while for the missing data of longer-term (e.g., more than 12 hours), the climate data from other weather stations that are close to the objective weather station in the same city will be used to be merged into the whole time-series dataset. The climate data from other the reanalysis dataset are merged into the long-term dataset of the objective weather station location. The general climate conditions for air temperature, relative humidity, global horizontal radiation, and wind speeds of the 12 cities in the summer over the 31 years are plotted in Figure 2. The first two largest cities, Toronto and Montreal, have the highest mean air temperature during summer months (i.e., May to September) over this period, and the fourth largest city, Ottawa, is similar to that of Montreal. Due to the sea breeze on the west coast in the summer, the third-largest city in Canada, Vancouver, has a much lower air temperature in summer. The other four cities in zone 6A, Charlottetown, Halifax, Moncton, and St. John's, all cities located on the east coast, may have lower air temperature, higher relative humidity, and higher wind speed than the other two cities, Montreal and Ottawa, in the same climate zone. The four cities (Winnipeg, Saskatoon, Calgary, Whitehorse) in the very cold climate zone (i.e., climate Zone 7) may have greater air temperature variations because their locations differ greatly from south to north. They also have higher wind speed and lower relative humidity. The four largest cities, Toronto, Montreal, Vancouver, Ottawa, and the three cities in the very cold zone, Winnipeg, Saskatoon, and Calgary, have relatively higher global horizontal radiation. The variation of climate variables over the 31 years is further discussed in the results section. The current study assumes the climate condition at the weather stations represents the climate in the city, so the urban heat island effect in the city cannot be fully considered. Our future work will adopt a high-resolution regional climate model (RCM) to enable more detailed consideration of the spatial variation of the climate condition in each city.

Building simulation

Two types of buildings were considered in this study: school and office buildings (Figure 3). The ASHRAE standard 90.1 for commercial building reference model (ASHRAE 2013) has been used in this study to evaluate the indoor overheating condition in the 12 cities in Canada. The building configuration of the model was also changed for the four climate zones in Canada to the design conditions of the 12 different cities, following that given in the ASHRAE Handbook of Fundamentals (ASHRAE 2009). The HVAC systems in these building models were removed to mimic the building’s freerunning conditions.

The total building area in this study is 6871 m² for the primary school and 511 m² for the small office building. The thermal zone of the school building has been divided by the function of the rooms to consider the different classrooms, office, computer classroom, and cafeteria, etc. The thermal zone of the office room has been divided based on the orientation of the room and also a core thermal zone in the centre region.

Table 2 Building envelope of reference building models.

<table>
<thead>
<tr>
<th>Bldg. Type</th>
<th>Cli. Zone</th>
<th>R-value (m²·K/W)</th>
<th>U-Factor (W/m²·K)</th>
<th>SHGC</th>
</tr>
</thead>
<tbody>
<tr>
<td>office</td>
<td>Ex. walls</td>
<td>5.18</td>
<td>6.52</td>
<td>N/A</td>
</tr>
<tr>
<td>4C</td>
<td>Roof</td>
<td>3.24</td>
<td>N/A</td>
<td>0.39</td>
</tr>
<tr>
<td>5A</td>
<td>Window</td>
<td>3.24</td>
<td>N/A</td>
<td>0.39</td>
</tr>
<tr>
<td>6A</td>
<td>Skylight</td>
<td>3.24</td>
<td>N/A</td>
<td>0.39</td>
</tr>
<tr>
<td>school</td>
<td>Window</td>
<td>7.96</td>
<td>6.52</td>
<td>N/A</td>
</tr>
<tr>
<td>4C</td>
<td>Skylight</td>
<td>3.24</td>
<td>N/A</td>
<td>0.49</td>
</tr>
<tr>
<td>5A</td>
<td>Window</td>
<td>3.24</td>
<td>N/A</td>
<td>0.385</td>
</tr>
<tr>
<td>6A</td>
<td>Skylight</td>
<td>3.24</td>
<td>N/A</td>
<td>0.385</td>
</tr>
<tr>
<td>7</td>
<td>Window</td>
<td>2.75</td>
<td>2.79</td>
<td>0.487</td>
</tr>
<tr>
<td>school</td>
<td>Skylight</td>
<td>2.75</td>
<td>2.79</td>
<td>0.487</td>
</tr>
</tbody>
</table>
Assessment method

Multiple overheating assessment methods were collected from existing studies in different countries. The method to define indoor overheating conditions can be different for building occupants in different countries and regions. However, the existing overheating assessment methods provide the method to describe the overall indoor thermal pattern in summers.

Most of the overheating criteria are based on the indoor air temperature or the operative temperature to develop a static or adaptive temperature threshold to identify overheating hours. A few of the newer studies proposed the thermal comfort and heat stress index, for which the heat stress index considers the human body's physiological thermal response to heat (Laouadi et al. 2020). This paper uses, however, only the (operative) temperature-based criteria to evaluate overheating in buildings located in Canadian cities. Both criteria with fixed and adaptive temperature thresholds are used and compared.

For the fixed temperature criteria used in this study, four (4) temperatures thresholds were considered based on different existing overheating assessment criteria: 25 °C, 26 °C, 28 °C, 30 °C, and 32 °C. The temperature threshold of 25 °C is obtained from the Passive House Institute (PHI) (PHI 2016). The fixed operative temperatures of 26 °C and 28 °C were also widely used for defining multiple overheating criteria. In CIBSE Guide A, the indoor temperature should not exceed 26 °C and 28 °C for 1% of the annual occupied hours for bedrooms and living rooms in residential buildings (CIBSE 2011), and CIBSE TM52 and TM59 (CIBSE 2013, 2017), the fixed temperature of 28 °C is used for school and office buildings. In EN16798-2019, the indoor operative temperature of mechanically ventilated or cooled zones, a fixed operative temperature of 26°C is used to define overheating (BS EN 16798 2019). As described in Building Bulletin 101, there is a requirement that the air temperature in classrooms during occupied hours should not exceed 32°C.

For adaptive comfort criteria, the temperature limit is usually a function of the outdoor running mean temperature. The CIBSE (CIBSE 2013) employed the adaptive thermal comfort levels defined by the European Standard EN 16798-2019 (BS EN 16798 2019), in which three (3) categories of comfort level are identified based on the predicted comfort temperature:

\[ T_{\text{comb}} = 0.33T_{\text{rm}} + 18.8 \]  

where, \( T_{\text{rm}} \) is the running mean daily average temperature, estimated by:

\[ T_{\text{rm}} = (T_{\text{ed}-1} + 0.87T_{\text{ed}-2} + 0.6T_{\text{ed}-3} + 0.5T_{\text{ed}-4} \]
\[ + 0.4T_{\text{ed}-5} + 0.3T_{\text{ed}-6} + 0.2T_{\text{ed}-7})/3.8 \]

and where \( T_{\text{ed}-1} \) is the daily mean external temperature for the previous day, \( T_{\text{ed}-2} \) is the daily mean external temperature for the day before, and so on.

Figure 4 Mean temperature over the 5 months May, June, July, August, and September in 12 cities and the trend in 31 years, shade shows the range between the maximum and minimum values.
The upper limits of the three (3) categories of thermal comfort are used for the evaluation of overheating in this study:

Cat 1: \( T_{\text{cat1\_upper}} = 0.33T_m + 18.8 + 2 \)  
(3)

Cat 2: \( T_{\text{cat2\_upper}} = 0.33T_m + 18.8 + 3 \)  
(4)

Cat 3: \( T_{\text{cat3\_upper}} = 0.33T_m + 18.8 + 4 \)  
(5)

The ASHRAE standard 55 has also similarly defined an adaptive thermal comfort, with the upper operative temperature limit defined as

\[ T_{\text{ASHRAE\_upper}} = 0.31T_m + 21.3 \]  
(6)

It can be noted that the ASHRAE thermal comfort upper limit is close to the upper limit definition for Category 1 thermal comfort given in BS EN 16798.

**Results**

**Comparison of indoor and outdoor variations**

After the 31-year simulation of the two building types, the mean indoor operative temperature of the buildings in 12 cities was summarized and is given in Figure 4. The overall mean indoor operative temperature in schools is around 2.5°C higher than the mean temperature in office buildings. This might be due to the higher internal heat gain in classrooms than that in office rooms and the higher R-value of school buildings' external walls. Indoor operative temperatures are highly affected by the local outdoor weather conditions, especially the local air temperature. The outdoor air temperature is also compared with the indoor temperatures in Figure 4. As might be expected, the mean indoor operative temperature is higher than the outdoor temperature, and the temperature range is much smaller than that outdoors.

The lines of linear regression given in Figure 4 show the mean temperature variation trend over the 31 years. Shade shows the range between the maximum and minimum values.

**Figure 5** Variation of mean a) global horizontal radiation and b) wind speed over the 5 months of May, June, July, August, and September in 12 cities and the trend in 31 years, shade shows the range between the maximum and minimum values.
by the warming climate. Toronto has the highest increasing trend of all the cities studied, followed by Montreal. Both the outdoor and indoor mean temperature for Toronto in 2016 is the highest.

The indoor operative temperature within buildings located in each of the 12 cities shows a similar trend compared to the corresponding outdoor conditions, but the mean indoor temperature is closer among different cities. The increasing and decreasing trend of mean values may change when it comes to indoor conditions. For example, even though the outdoor air temperature of Charlottetown, St Johns, and Winnipeg has an increasing trend over the 31 years, the indoor operative temperature of school buildings shows a decreasing trend; this suggests that the current type of building construction in these cities may still have the ability to resist a warming climate. The indoor conditions might also be affected by other climate variables.

Figure 6 Number of hours exceeding the fixed overheating criteria in the 12 cities over the 31 years.

Figure 7 Number of hours exceeding the adaptive overheating criteria in the 12 cities over the 31 years.
overheating occurrences in buildings are considered. For office buildings, very few hours can be identified as being at thermal comfort levels, for which the frequency and duration of overheating hours based on adaptive thermal comfort levels, and Figure 7 shows the overheating hours based on fixed thermal comfort thresholds and adaptive thermal comfort levels. The variation of Figure 6 shows the overheating hours based on fixed thermal comfort thresholds and adaptive thermal comfort levels. The variation of overheating conditions in 12 cities in the same region.

Whitehorse is around 1 ~ 1.5 °C lower than the other 3 cities located on the east coast of Canada. For climate Zone 7, the climate conditions of the cities found in these 3 cities located on the east coast of Canada. For climate Zone 7, the climate conditions of the different cities located in this zone are quite different from each other. Still, the three cities’ indoor operative temperatures in Winnipeg, Saskatoon, and Calgary are at the same level, and the indoor operative temperature of Whitehorse is around 1 ~ 1.5 °C lower than the other 3 cities in the same region.

Overheating conditions in 12 cities

Multiple overheating methods have been applied to the building simulation results for the overheating evaluation. Figure 6 shows the overheating hours based on fixed thermal comfort levels, and Figure 7 shows the overheating hours based on adaptive thermal comfort levels, for which the frequency and duration of overheating occurrences in buildings are considered. For office buildings, very few hours can be identified as being higher than 30°C, whereas schools are exposed to more severe overheating conditions. The variation of overheating hours having different temperature thresholds may exhibit different trends for the same city. But 7 of the 12 cities (Toronto, Montreal, Ottawa, Moncton, Halifax, Calgary, and Whitehorse) show the increasing trend in overheating of school buildings using different temperature thresholds, and this occurs for office buildings in 6 of the cities (Toronto, Montreal, Ottawa, Moncton, Charlottetown, Halifax).

On the other hand, the overheating results calculated by the adaptive thermal comfort levels exhibited a different result. It can be found that the overheating results calculated from the BS EN Category 1 and ASHRAE upper limits have almost the same overheating level. While most cities have a decreasing trend in overheating hours, and in Figure 7, only the school buildings in Halifax and both building types in Saskatoon show an increasing trend over the 31 years variation. The adaptive overheating criteria adopted in this paper are based on the assumption that the occupants may adapt to the higher temperature when the outside temperature is getting higher. Therefore, the temperature threshold will also be higher when the outside temperature is higher. This helps explain why, in most cities, the number of hours higher than the adapted temperature threshold does not increase, even though they mean temperatures in these cities are increasing. The hours with increased temperature may still have a lower temperature than the changing temperature threshold unless the increasing trend indoor temperature is stronger than the increasing trend of the adaptive temperature threshold.

Figure 8 shows the cooling degree hours (CDH) calculated with the different base temperature thresholds. It is defined as the cumulative overheating hours identified by the operative temperature above the threshold discomfort temperature weighted by the magnitude of the operative temperature exceedance. The CDH value evaluates the duration and frequency of the calculated overheating hours and the intensity of overheating above the thermal comfort thresholds. The result also shows the different variation trends of using fixed thermal comfort thresholds and adaptive thermal
comfort thresholds. Most of the upward regression lines come from the calculations using fixed thresholds, whereas the adaptive thermal comfort thresholds may lead to a downward trend over the 31 years from 1986 to 2016, which is similar to the observed trend of the overheating hours in Figure 7.

Conclusion

In this study, the building simulations capture the variation overheating conditions within the school and office buildings when subjected to long-term historical weather for buildings in 12 Canadian cities. The trend in overheating occurrences in buildings is captured by assessing building simulation results under freerunning conditions. The variation of the mean indoor operative temperatures during the summertime months are compared with the corresponding outdoor weather conditions, and for the outdoor air temperature, two cities, Vancouver and Saskatoon, a decreasing trend is observed. Most of the indoor operative temperature trends over the 31 years studied are consistent with the outdoor air temperature variations. It was also determined that the outdoor temperature is the most sensitive factor affecting the indoor operative temperature within buildings. But there are also exceptions, for example, like those found in Charlottetown, St Johns, Winnipeg, and Saskatoon, in which the effect of solar radiation and wind speed on the indoor thermal environment is more pronounced than that of the outdoor temperatures.

Multiple existing overheating assessment methods, including the fixed temperature threshold and adaptive thresholds, were also applied and compared. It was found that the overheating hours, calculated by using fixed overheating criteria, were different from those calculated by the adaptive thermal comfort criteria. The use of fixed criteria captures the increasing trend of indoor overheating in most of the cities studied. It is also surprising that the overheating hours calculated using the adaptive thermal comfort criteria have a decreasing trend for most cities. Note that adaptive criteria are based on the assumption that people might be more resistant to a higher temperature when exposed to the relatively warmer environment estimated only by the daily running-mean temperature. This implies that the overheating criteria are critical parameters in estimating the risk of overheating in buildings. Thus, it is crucial to explore indoor overheating using physical bio-heat thermal comfort models to evaluate the practical impact on building occupants. In future work, the sensitivity of building models to different climate variables will be explored. The study will also be continued by using the bias-corrected future projected climate data from the regional model CanRCM4 database downscaled from a large ensemble of its global parent model, CanESM2, to explain further the effect of climate change over a much longer time frame. Different overheating mitigation strategies will also be evaluated based on the future projected climate data.

Acknowledgment

The research was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) the “Advancing Climate Change Science in Canada Program” [#ACCPJ 535986-18], the Construction Research Centre of the National Research Council of Canada, from the support of Infrastructure Canada and the Pan Canadian Framework on Clean Growth & Climate Change.

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Proceedings of the 17th IBPSA Conference
Bruges, Belgium, Sept. 1-3, 2021
https://doi.org/10.26868/25222708.2021.31024