A field study on summertime overheating of six schools in Montreal Canada

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Abstract: Due to global climate change, the world has been experiencing significant increases in average temperatures and the frequency and intensity of extreme weather events such as heatwaves. The overheating problem in indoor spaces of buildings has become a concern to the comfort and health of building occupants, especially vulnerable populations such as the elderly, children, or the sick. A field monitoring network consisting of rooftop weather stations and indoor sensors has been set up on 11 buildings of different types in Montreal, Canada. This paper presents the results of field measurements of indoor thermal conditions of six school buildings to assess the risks of summertime overheating. These six primary school buildings were built in 1930-1966 with window-wall-ratios between 10-30% and limited mechanical ventilation. The indoor dry-bulb air temperature, relative humidity, and CO₂ concentrations are measured by indoor wireless sensors. The weather conditions, including dry-bulb temperature, relative humidity, solar radiation, rainfall, wind speed, and wind direction, are measured by rooftop weather stations. Measurements presented in this paper are collected from July to September 2020, which include four different time intervals: (a) during two heatwaves, (b) during summer break when schools were closed, and (c) when schools were reopened, and windows were intermittently opened. Data analysis shows that the indoor and outdoor temperature difference has a strong linear correlation with the outdoor temperature observed for all school buildings. This correlation is also affected by building operations, such as opening windows, closing blinds, and the micro-climate of their surroundings.

1. Introduction

Global climate has been consistently warming over the past decades and is projected to worsen in the future. Extreme climate events such as heatwaves are also projected to increase in frequency and intensity [1, 2]. As a result, the overheating of building interior spaces has been a major concern to the comfort and health of building occupants, particularly the vulnerable people such as the elderly, children, the physically challenged, or the sick. In Montreal, following a recent heatwave (June 30 - July 7, 2018), up to 53 deaths were reported, with most of those being elderly and people who suffered from mental or chronic illness. Building overheating has been extensively studied in the past, mostly for residential buildings [3-12], some for social housing buildings [13, 14], and school buildings [15]. It has been found that overheating was common in modern buildings of all types [7,14]. A higher chance of overheating was found for top floors than ground floors of the apartment buildings, detached houses, and in the properties constructed after 1995. Most of these properties have no mechanical ventilation. It
is demonstrated that the measures such as increased ventilation, nighttime ventilation, and various shading schemes could mitigate overheating significantly [14].

As one of the tasks of a multi-year research project on the assessment and mitigation of overheating in buildings housing vulnerable people in Canada, field monitoring of 11 buildings in Montreal has been carried out including schools, long-term care facilities, and senior homes. This paper presents the field measurement results over the summer of 2020, covering the heatwave periods in six school buildings.

2. Methodology

2.1 Description of selected buildings

The six selected schools in Montreal (Figure 1) are low-rise buildings up to three stories, built in 1930-1966 with window-wall-ratios between 10-30%. Among all these selected schools, only School-3 has a mechanical ventilation system installed to provide outdoor air and utilize the nighttime free cooling, while all the other schools have no central air conditioning or mechanical ventilation systems. Figure 2 shows an example of one school’s floor plan with the rooms selected for monitoring. These classrooms were selected according to different orientations for comparison purposes. Details about the selection criteria and selected buildings are provided in [16]. This paper reports the measurements from School-1 as an example of detailed discussion.

2.2 Instrumentation

Weather stations are installed on the rooftops to monitor on-site weather conditions. An outdoor RHT sensor measures outdoor temperature and relative humidity with an accuracy of ±0.21°C in temperature and ±2.5% in relative humidity, and solar radiation is measured by a pyranometer with an accuracy of ±10 W/m². On average, four rooms per school building are instrumented to measure indoor air temperature with an accuracy of ±0.21°C, relative humidity (RH) with ±2.0%, and CO₂ levels with ±50ppm. For all the indoor and outdoor sensors, the sampling frequency is five minutes, and all the data were averaged over 5-minutes and reported hourly in this paper.

2.3 Data analysis

To investigate the response of buildings to the outdoor conditions, correlation models between the indoor conditions and outdoor temperature and sol-air temperature are developed. Different correlations were investigated, including indoor temperature or temperature difference between indoor and outdoor as dependent variables.

Several standards and procedures are often used to assess indoor thermal comfort, including American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 55-2017 [17], the British Standard European Norm (BS EN) Standard 15251:2007 [18], and technical memorandum (TM) 52 and the updated 59 [19, 20] from the Chartered Institute of Building Services Engineers (CIBSE). The ASHRAE adaptive criterion is used in this study, which relates the indoor thermal comfort to the prevailing outdoor conditions under the assumption that occupants’ thermal expectations are influenced by recent weather conditions. The number and percentage of hours according to the ASHRAE adaptive criteria are also analyzed for the monitored buildings. A weighted
running mean daily outdoor temperature is used as the independent variable, which is calculated over the last seven up to 30 days prior to the day in question.

3. Results

3.1 Data collection time intervals
Here, a heatwave period is defined as three consecutive days with weighted moving average temperature exceeding 31°C [21, 22]. As a result, two heatwaves were recorded from July 23 to July 25 and from August 12 to August 14, 2020. Four distinctive time intervals (TI) were selected for analysis using the following criteria: (a) during two heatwaves, (b) during the summer break when the schools were closed, and windows were closed, and (c) when schools reopened (after August 26, 2020):

1) TI-1 (July 24 to July 30): One-week period including the first heatwave with an average outdoor temperature of 30.3°C.
2) TI-2 (August 2 to August 8): The period between the two heatwaves with a lower average outdoor temperature of 29.1°C.
3) TI-3 (August 10 to August 16): One-week period including the second heatwave with an average outdoor temperature of 30.2°C.
4) TI-4 (August 27 to September 3): The first week after the reopening of schools, when windows were intermittently opened, and the average outdoor temperature sharply decreased to around 18°C.

Figure 3 presents the hourly outdoor temperature ($T_{\text{out}}$) and solar radiation intensity recorded by the weather station at School-1. The four time-intervals are marked with different background colors.

![Figure 3. Outdoor temperature and solar radiation measured at School-1 from July 18 to September 30](image)

3.2 Indoor temperature versus outdoor temperature

Figure 4 shows the derived relationship between indoor and outdoor air temperatures in room 301 for the four time-intervals. The first model of the hourly indoor and outdoor air temperatures (Figure 4a) shows a weak correlation, $R^2 = 0.04 \sim 0.42$. In comparison, the second model based on the temperature difference $\Delta T$ and the outdoor air temperature (Figure 4b) shows a much better correlation: $R^2 = 0.95 \sim 0.99$. Here,

$$\Delta T = a \cdot T_{\text{out}} + b$$

(1)

$$\Delta T = T_{\text{in}} - T_{\text{out}}$$

(2)

Both the coefficients $a$ and $b$ values are similar for the periods of TI1-TI3, which indicates similar responses of the building to the outdoor conditions. Although TI-4 showed a more scattered distribution due to the occupant activity when the school was reopened, the $R^2$ value remains close to 1.0. The smaller coefficient $b$ is most likely caused by the lower outdoor temperature and opening windows.

The correlation of $\Delta T - T_{\text{out}}$ is better (Figure 4b), so it was used for the analysis in the four rooms with different orientations: 301, 302, 305, and 306 (Figure 5). Room 305 has a higher average indoor temperature during the TI-1 heatwave period, and the highest indoor temperature of 33.9°C appeared on July 28. The average indoor temperatures are the lowest after the school reopens. The constant
coefficient \( a \) in all rooms and all time-intervals are within the range of -0.80 to -0.99, while the \( R^2 \) values are within the range of 0.86 to 0.99.

![Figure 4](image_url)

**Figure 4.** Correlations for room 301 at School-1: (a) indoor temperature vs outdoor temperature, (b) temperature difference between indoor and outdoor vs outdoor temperature

![Figure 5](image_url)

**Figure 5.** Correlations of indoor and outdoor temperature vs outdoor temperature in classrooms 302, 305, and 306 at School-1

Similar trends are found in other school buildings. For all 22 classrooms monitored in the six school buildings, the coefficient \( a \) is in a range of 0.77 to 0.99 with \( R^2 \) values in the range of 0.83 to 0.99. The coefficient \( b \) shows a greater difference between rooms, in a range of 16.7 to 24.1; in all cases, the coefficients \( b \) after school reopening are lower than before school reopening, which indicates a lower indoor temperature.

### 3.3 Indoor air temperature versus sol-air temperature

![Figure 6](image_url)

**Figure 6.** (a) Indoor temperature vs sol-air temperature, (b) temperature difference between indoor and outdoor temperatures vs sol-air temperature during the daytime

The correlation model is represented as: \( \Delta T = c \cdot T_{sol-air} + d \) (3)

where \( T_{sol-air} \) is sol-air temperature, which is calculated according to ASHRAE Handbook Fundamentals [23], \( \Delta T \) is defined in equation (2).
As shown in Figure 6(a), plotting $T_{in}$ vs $T_{sol-air}$ results in low $R^2$ values, whereas plotting $\Delta T$ vs $T_{sol-air}$ (Figure 6b) provides better $R^2$ values. The nighttime sol-air temperature is the same as the outdoor temperature, therefore, not presented here.

For all 22 rooms monitored in the six school buildings, the daytime coefficient $c$ has values in the range of 0.21 to 0.39, and $R^2$ values in the range of 0.35 to 0.77. The $R^2$ values in TI-2 are much higher than the other time-intervals, which shows a better correlation. The average solar radiation in TI-2 is much lower than in TI-1 and TI-3 during the heatwave. The low $R^2$ in TI-4 may be caused by adjusting and opening of curtains.

The high-value coefficient $a$ and $R^2$ indicate that outdoor temperature is the most significant factor affecting the indoor thermal conditions and the indoor and outdoor temperature difference. Solar radiation is another affecting factor, but less significant compared to outdoor temperature and the correlation between indoor and outdoor temperature difference with sol-air temperature is not as strong, indicated by smaller coefficient $c$ and $R^2$ values.

### 3.4 Indoor thermal condition assessment

Figure 7 shows the hourly indoor air temperature measurements of four rooms (301, 302, 305, and 306) in School-1 from July 18 to September 30 versus the prevailing mean outdoor air temperature. The 80% acceptability limit range of thermal comfort according to the ASHRAE adaptive thermal comfort model is presented [17]. The exponentially weighted moving average (EWMA) with $\alpha=0.8$ is used for calculating the prevailing mean outdoor air temperature. A seven-day calculation period was used in this study. The results show that for a prevailing mean temperature under 22°C the indoor temperature is mostly under the upper 80% acceptability limit, whereas for prevailing mean temperature over 24°C the indoor temperature is mostly over the upper 80% acceptability limit.

![Figure 7. Hourly indoor temperature measurements at School-1 on the ASHRAE adaptive chart with 80% acceptability limit range](image)

Figure 8 presents the percentage of overheating hours before (from July 18 to August 26) and after (from August 27 to September 30) school reopening. There is no overheating after school opening. Before school reopening, the windows in all classrooms are kept closed and the interior shading was down. Room 305 has the highest overheating hour among the four classrooms, while Room 306 has the lowest overheating hours. It is important to note that the indoor measurements in room 306 during TI-3, which may have been affected by the construction work on the southeast façade, have lower values and fewer fluctuations than the data from other rooms. Rooms 305 had zero overheating hours after school re-opening probably due to the windows opening although this room during the summer break had the highest overheating hours.

The overheating hours during the day and at night are similar; because the windows were closed at night, and the heat was stored in the building thermal mass; as a result, the indoor air temperature stayed high. The problem does not exist in School-3 that uses mechanical ventilation for free cooling at night.
Figure 8. Percentage of overheating hours at School-1 before and after school re-opening

Figure 9 presents the percentage of overheating hours of total daily hours as a function of prevailing mean outdoor temperature range, before and after School-1 re-opening. As the prevailing mean outdoor air temperature increases, the percentage of overheating hours increases as well. Before school re-opening, the prevailing mean outdoor air temperature is always above 20°C, while after the school reopens, it is always lower than 22°C. For outdoor air temperature over 20°C, overheating is present over 80% of the time in rooms 301, 302, and 305. Overheating is present almost exclusively in the period before school reopens. After school is reopened, windows are intermittently opened for better thermal comfort and for increased ventilation to address health concerns, as the measurements in TI-4 were taken when the school reopened during the COVID-19 pandemic.

Figure 9. Percentage of overheating hours at School-1 as a function of the prevailing mean outdoor temperature range

Table 1 presents the overheating hours and percentage of total daily hours, calculated for each time interval for the six school buildings investigated. TI-4 period (after school reopened) has much lower overheating hours over all the selected time intervals. The period TI-2 (before the heatwave) has lower overheating hours than TI-1 (heatwave with high outdoor temperature) and TI-3 (after heatwave). Rooms with a high window-wall-ratio have a higher chance to have an overheating problem, such as room 60 at School-3, room 204 at School-4, and room 114 at School-6. These rooms are activity rooms with large window sizes and oriented to the south. Compared to other classrooms in the same building, the percentage of overheating of these rooms is significantly higher.

Table 1. Overheating hours and the percentage of total daily hours for each time interval for six school buildings

| Room number | School-1 | School-2 | School-3 | School-4 | School-5 | School-6 |
|-------------|----------|----------|----------|----------|----------|----------|
| 301         | 0        | 0        | 168      | 0        | 0        | 0        |
| 302         | 0        | 0        | 168      | 0        | 0        | 0        |
| 305         | 0        | 0        | 168      | 0        | 0        | 0        |
| 306         | 0        | 0        | 168      | 0        | 0        | 0        |
| 200         | 0        | 0        | 168      | 0        | 0        | 0        |
| 203         | 0        | 0        | 168      | 0        | 0        | 0        |
| 208         | 0        | 0        | 168      | 0        | 0        | 0        |
| 212         | 0        | 0        | 168      | 0        | 0        | 0        |
| 14          | 0        | 0        | 0        | 0        | 0        | 0        |
| 23          | 0        | 0        | 0        | 0        | 0        | 0        |
| 34          | 0        | 0        | 0        | 0        | 0        | 0        |
| 60          | 100      | 100      | 100      | 0        | 0        | 0        |
| 108         | 70        | 55        | 90        | 0        | 35        | 36        |
| 120         | 0        | 0        | 0        | 0        | 0        | 0        |
| 201         | 0        | 0        | 0        | 0        | 0        | 0        |
| 204         | 0        | 0        | 0        | 0        | 0        | 0        |
| 112         | 0        | 0        | 0        | 0        | 0        | 0        |
| 113         | 0        | 0        | 0        | 0        | 0        | 0        |
| 114         | 0        | 0        | 0        | 0        | 0        | 0        |
| 185         | 0        | 0        | 0        | 0        | 0        | 0        |
| 167         | 0        | 0        | 0        | 0        | 0        | 0        |
| 172         | 0        | 0        | 0        | 0        | 0        | 0        |
| TI-1 Overheating hours | 168 | 168 | 168 | 168 | 168 | 168 |
| TI-2 Overheating hours | 100 | 100 | 100 | 100 | 100 | 100 |
| TI-3 Overheating hours | 103 | 101 | 103 | 106 | 106 | 106 |
| TI-4 Overheating hours | 61.3 | 60.1 | 97 | 87.5 | 100 | 98.8 |
| TI-5 Overheating hours | 158 | 168 | 168 | 122 | 168 | 168 |
| TI-6 Overheating hours | 94 | 100 | 100 | 100 | 100 | 100 |
| TI-7 Overheating hours | 0 | 3 | 0 | 0 | 0 | 0 |
| TI-8 Overheating hours | 1.79 | 1.79 | 1.79 | 1.79 | 1.79 | 1.79 |
4. Discussion and conclusions

The comparison of results from the six school buildings over four time-intervals (TIs) shows a similar pattern. The highest overheating hours were recorded during the two heatwaves periods TI-1 and TI-3. In the worst case, the percentage of overheating hours could reach 100%, which could impose risks to the health of vulnerable populations such as primary school students. The overheating issue could last long after the heatwave. In the period between two recorded heatwaves (TI-2), the number of overheating hours is still high while the outdoor temperature has decreased. Since the percentage of overheating hours decreases with the prevailing mean outdoor temperature, the situation gets better in late summer (TI-4); also, the severity of overheating risk among selected rooms may change due to occupants' activity in this period.

Among the school buildings investigated, there is a high percentage of overheating hours at night, which is almost as high as that of the daytime, especially in old buildings. The issue could be mitigated by increasing ventilation, such as opening the windows and using mechanical ventilation systems with an appropriate control strategy, such as free cooling.

Due to COVID 19, schools were closed in Montreal from mid-March to the end of August 2020. Hence, the impact of overheating during regular school hours was not fully monitored. We are continuing the field measurements and data to be collected during summer 2021 will be analyzed and reported in the future. These measurements will be analyzed to identify building design and operation parameters contributing to the overheating issues in these buildings, develop correlation-based models to predict thermal responses of buildings and assess indoor overheating risk due to forecasted heat waves or future climates and help develop mitigation strategies.

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