Chapter 259
Comparing Multiple Overheating Assessment Metrics Using Measured Data

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Abstract In this study, a comparison is made of overheating in multiple field-monitored buildings using several different overheating indices, including dry-bulb temperature, the heat index (HI), humidex (H), standard effective temperature (SET), wet-bulb globe temperature (WBGT), discomfort index (DI), and summer simmer index (SSI). The field monitoring was conducted in the city of Montreal, Canada over the summer of 2020 at six school buildings and two hospital buildings. In at least two typical rooms of each building, temperature and humidity sensors were installed; a total of 34 rooms were instrumented in these 8 buildings, and the rooms are facing different orientations and are located on different floors. The extent of concordance amongst the different overheating metrics was examined by correlation analysis. The result from this study provides an evaluation of the similarity between the different assessment metrics and helps identify the assessment approach that is the most representative of the methods evaluated.

Keywords Field monitoring · Overheating · Correlation analysis · Heat index · Standard effective temperature · Humidex

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259.1 Introduction

A severe heatwave in 2018 happened in Montreal resulted in 66 heat-related (Shu et al. 2020; Leon et al. 2020). Many studies from Europe have conducted urban-scale or national-scale field monitoring on building overheating (Chen 2019), while there are still limited studies from other regions or countries, including Canada. To figure out the overheating in the current building stocks in Montreal and predict the future overheating potentials, an urban-scale field study of the different building types was conducted to collect measured data in real buildings. The overheating assessment criteria are quite different in different regions and countries. In theory, any thermal comfort index can be used to describe thermal conditions in buildings and reflect overheating conditions. Laouadi et al. (2020) summarized existing overheating criteria and found most of them use temperature-based metrics. A bio-heat thermal index, standard effective temperature (SET), is therefore proposed for evaluation of overheating in Canada (Laouadi et al. 2020; Ji et al. 2021). However, many other thermal indices can evaluate thermal conditions in buildings, while there is still a lack of study comparing different thermal indices.

259.2 Methods

259.2.1 Building Selection and Instruments

The field study was conducted in the selected buildings in Montreal through building surveys and on-site visiting (Shu et al. 2020; Leon et al. 2020) and the data in 2020 for 2 hospitals and 6 schools (from 3 school boards) are used in this study. Weather station tripods were installed on the roofs of the buildings to measure the local weather conditions (Fig. 259.1). The weather stations are using the RX3004 logger from HOBO Onset, with LCD and GSM/HSPA cellular communications so that the data can be downloaded remotely. The operating weather stations are composed of temperature and humidity sensors (S-THB-M002), pyrometers (S-LIB-M003), wind speed (RM Young Wind Monitor Sensor) and direction (RM Young Wind Monitor Sensor) sensors, and rainfall sensors (S-RGB-M002).

The indoor sensors were installed at 1.7 m above the floor which is the estimated height of adults. They are attached to the internal walls on the corridor side of the room to avoid direct solar irradiations. To avoid thermal interaction with indoor heat sources, the sensors were kept away from the electrical utilities, e.g., televisions, and refrigerators. Examples of the installed sensors are shown in Fig. 259.1b, c.

Fig. 259.1 Installations of the, **a** weather stations and **b, c** indoor sensors in buildings

259.2.2 Monitored Rooms and Data

The characteristics of the monitored rooms are summarized in Fig. 259.2. Among the selected 8 buildings, 33 rooms were monitored and evaluated, with 39% of them from hospitals and the rest from schools. During the on-site visit (Shu et al. 2020), most of the rooms that had an overheating problem were found on the top floor of the buildings, receiving more heat gain through the roof, so a greater portion of the rooms was selected from the top floor (79%) than those on the lower floors (21%). The orientations of the rooms are indicated by the directions of the vectors normal to their exterior walls. Most of the selected rooms facing the southeast (SE) and southwest (SW) are expected to be more vulnerable because of their longer exposure to solar radiation from the south (S) than the northern side, whereas rooms facing other directions are also covered in this study. Among the 33 rooms, only 24% of them have access to air conditioning, with most of them in hospitals, and few in schools. Only the third school board (SB3) has a well-controlled night cooling system in their building and a few of the hospital buildings only have mechanical ventilation in the activity room or waiting rooms, therefore, 85% of the rooms have no mechanical ventilation. The measured data from 2020-07-18 00:00:00 to 2020-08-07 00:00:00 (20 days in total) is used for the following analysis.

259.2.3 Overheating Assessment Criteria and Thermal Indices

There are many approaches for the evaluation of overheating in buildings, and different approaches use different threshold values, beyond which overheating is thereafter considered. These threshold values have been based on static or adaptive thermal comfort, heat stress level, or heat-related health outcomes of the building occupants. One common approach to assess overheating is using the number of hours above the chosen threshold value over an entire summer period. Most of the current

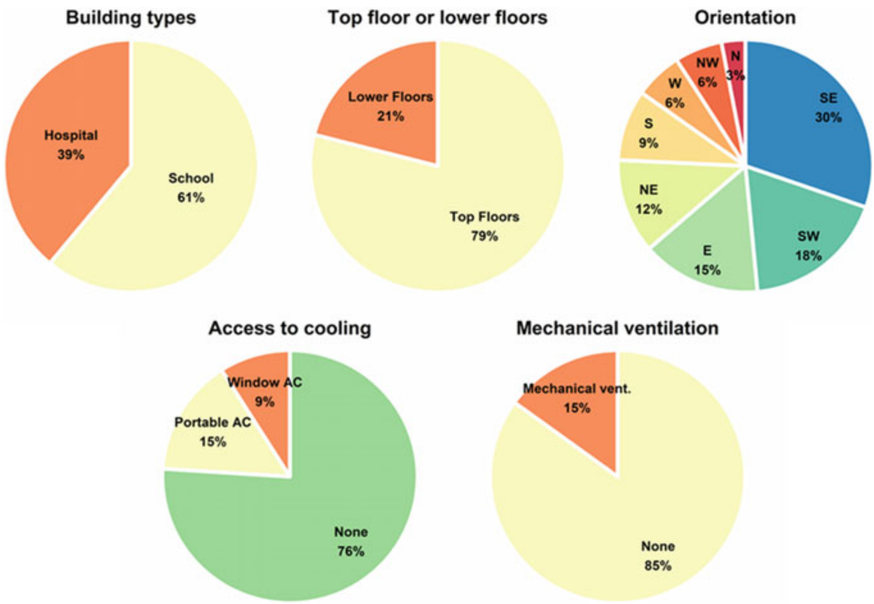


Fig. 259.2 Summary of the characteristics of the investigated rooms in the field monitoring

criteria are using only the air temperature (T) as the indicator of the building's indoor thermal or overheating condition, while studies show that the thermal sensation of the occupants can also be affected by other environmental variables such as humidity. In this study, several different overheating indices are considered for the comparison, including dry-bulb air temperature (T), the heat index (HI), humidex (H), standard effective temperature (SET), wet-bulb globe temperature (WBGT), summer simmer index (SSI), and discomfort index (DI). The threshold values for the calculation of overheating hours using different thermal indices are summarized in Table 259.1, the description of overheating risks is also quite different from the threshold values due to the page limit, please find the information from the reference in the list.

259.2.4 Correlation Analysis

The definitions of thermal indices, assessment scales, and descriptions of these assessment scales can be quite different as mentioned. After the overheating hours are calculated through the different indices and thresholds, Kendall's correlation analysis (Kendall 1938; Abdi 2008) is conducted on the percentage of overheating hours in the evaluated timeframe to reflect the degree of concordance for the 33

Table 259.1 Thermal indices and threshold values for overheating analysis

Thermal indices	Threshold values	Ref
T-Fixed	25, 28, 32 °C	CIBSE (2011); Zero Carbon Hub (2015); Department for Education Schools and Families (DfES) (2006); Department of Health (2007)
T-Adaptive	Cat 1: $T_{cat1_{upper}} = 0.33T_{rm} + 18.8 + 2$ Cat 2: $T_{cat2_{upper}} = 0.33T_{rm} + 18.8 + 3$ Cat 3: $T_{cat3_{upper}} = 0.33T_{rm} + 18.8 + 4$	BS En 16798 (2019)
H	20, 29, 35, 40, 45, 54	Havenith and Fiala (2016)
HI	26.7, 32.2, 41.6, 54.4 °C	National Weather Service (2021)
WGBT	22, 26, 29, 32 °C	ISO 7243 (2017)
SSI	28.3, 32.8, 37.8, 44.4, 51.7, 65.6 °C	Patania et al. (2015)
DI	21, 24, 27, 29, 32 °C	Poupkou et al. (2011); Siami and Ramadhani (2019); Giles et al. (1990); Matzarakis et al. (1991); Musco et al. (2016)
SET	25.6, 30.0, 34.5, 37.5 °C	Parsons (2007)

* T_{rm} is the outdoor running mean temperature calculated by the daily mean temperatures of the previous 1 to 7 days

rooms using different thermal indices and criteria. The overheating criteria are clustered based on the correlation coefficients to help identify the intrinsic connections between different thermal indices and criteria.

259.3 Results

259.3.1 Measured Data Analysis

The measured indoor air temperature and relative humidity are given in Fig. 259.3, and the evaluated percentage of overheating hours using the temperature-based criteria is in Fig. 259.4. The boxplot of the air temperature and relative humidity shows the ranges of these two variables in the rooms. Rooms with higher air temperatures tend to have a lower relative humidity in these observed results for these selected buildings.

The overheating conditions of the schools from the three different school boards (SB1, SB2 and SB3) are quite different (Fig. 259.4). Rooms from school boards 1 and 2 (SB1 and SB2) have severe overheating problems, while the situation is better in the building from school board 3 (SB3) due to the application of the night cooling

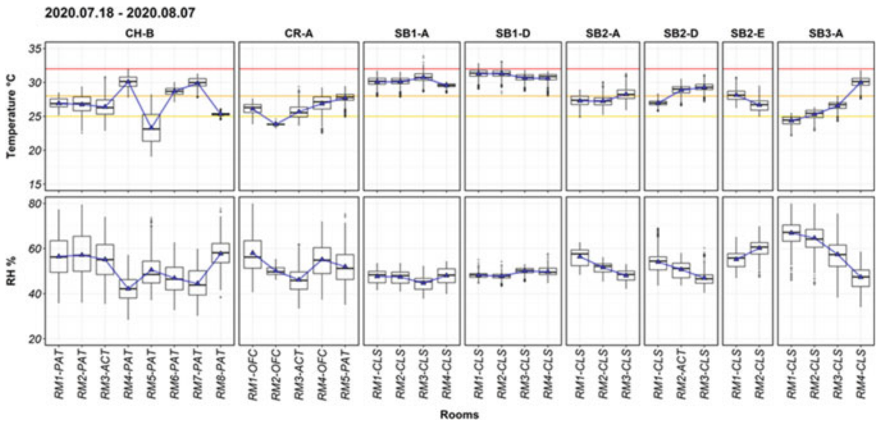


Fig. 259.3 Boxplot of the monitored indoor air temperature and relative humidity for the eight buildings

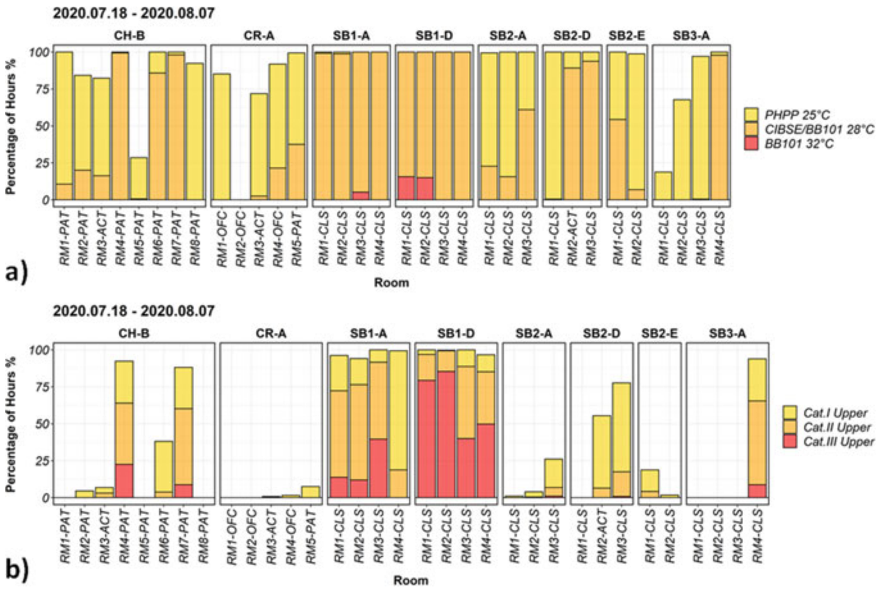


Fig. 259.4 Percentage of overheating hours in different buildings and rooms evaluated by, **a** the fixed temperature criteria and **b** the adaptive temperature criteria

system. The two schools SB1-A and SB1-D from the first school board SB1 have the most severe overheating compared to the others with their temperature higher than 28 °C for almost 100% of the time and some of the rooms even have a temperature higher than 32 °C (SB1-A [RM3-CLS], SB1-D [RM1-CLS, RM2-CLS]). For the hospital building CH-B, rooms RM4, RM6 and RM7 are those that have the most severe overheating problem with 80% of hours above 28 °C, and the other rooms RM1, RM3, RM 5 and RM8 with air conditioners and RM2 on the second floor of the building have no more than 20% of hours above 28 °C and no more than 10% of hours above the adaptive temperature threshold of BS EN. Another hospital building CR-A has generally been well-conditioned and had few overheating complaints during the survey and site-visiting, because they have fresh air and cooling supply to the hall and corridor area, and most of the rooms have a window AC installed. Three rooms, RM1, RM4, and RM5, are without AC installed, while RM2 and RM3 are typical rooms with a window AC. The patient room RM5 has the most severe overheating problem with more than 35% of hours above 28 °C, while it has only no more than 10% of an hour above the Cat I threshold of BS EN.

259.3.2 Comparison of Overheating Criteria

To further explore the concordance of the different thermal indices using their thermal limit thresholds or the assessment scales, the percentage of overheating hours in the 33 rooms is calculated using the different thermal stress thresholds. Figure 259.5 shows the distribution of the percentage of overheating hours evaluated by the different thresholds of the thermal indices. A significant difference can be noticed when the thresholds of the thermal indices are not too high. If the thresholds are selected to be too high, the percentage of overheating hours would be all 0 for the 33 rooms, for example, 40.6 °C or above for HI, 45 °C or above for H, 44.4 °C or above for SSI, 29 °C or above for DI, and 34.5 °C or above for SET. These thresholds are therefore excluded from the discussion in the following study.

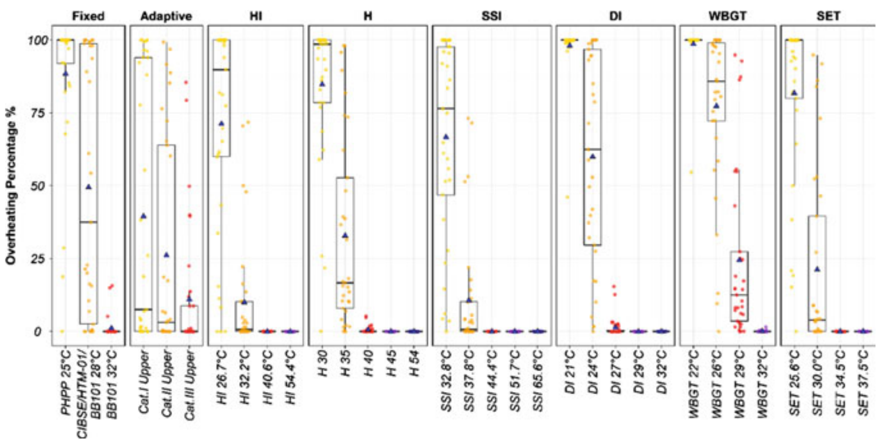


Fig. 259.5 Comparison of the overall ranges of the overheating evaluated by different assessment methods, jitter points show the value for each room

To explore the potential connections between the thresholds of the different thermal indices, a hierarchical clustering analysis has been conducted by the Euclidean distance of the correlation coefficients, and it clustered the criteria into 6 groups with different levels of overheating. The calculated Kendall's tau correlation coefficients are summarized, and the hierarchical clusters are outlined with red boxes in Fig. 259.6. The correlation between the different criteria and the mean air temperature is also provided in the first column as a reference to help understand the relationship of the different clusters with the mean air temperature. The coefficients inside of each of the clusters are positively strong, while the coefficients between the groups would be relatively weak, showing the evaluation of the 33 rooms is more concordant (tau ~ 0.7) when the threshold is at certain levels of the indices.

The first cluster is the criteria with extra-low-level thresholds (C-XL), which includes the DI 21 °C and WBGT 22 °C and their correlation with mean air temperature is also not strong. The second cluster is the criteria with the low-level threshold

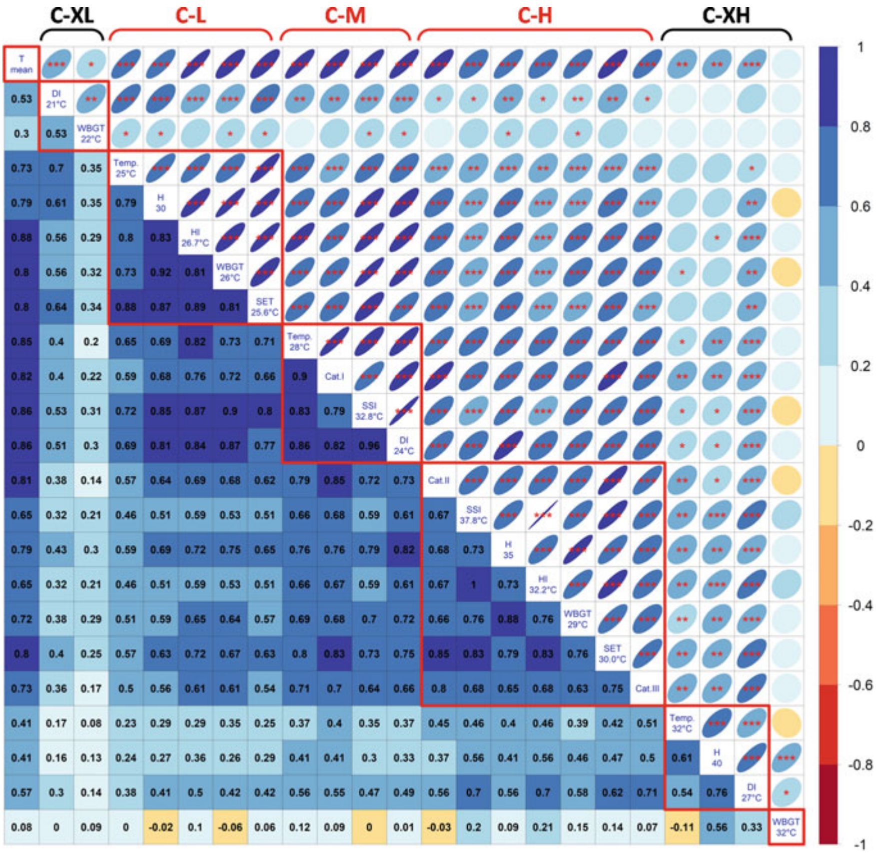
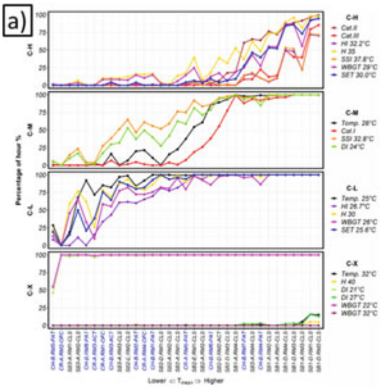


Fig. 259.6 Kendall's tau coefficient of evaluated overheating percentages between different criteria, the * signs indicate the significant levels: ***-p-value < 0.001, **-p-value < 0.01, * p-value < 0.5



b)

Group	Fixed °C	Adaptive Category	HI °C	H (°C)	SSI °C	DI °C	WBGT °C	SET °C
C-XL						21	22	
C-L1	25							
C-L2			26.7	30			26	25.6
C-M1					32.8	24		
C-M2	28	Cat I						
C-H1		Cat II		35			29	30.0
C-H2		Cat III	32.2		37.8			
C-XH	32			40		27	32	
Excluded Thresholds					44.4			
			40.6	45	51.7	29		34.5
			54.4	54	65.6	32		37.5

Fig. 259.7 **a** The percentage of overheating hours evaluated by the different clusters of criteria and **b** the map of the equivalency between the different criteria

(C-L), including the fixed temperature threshold of 25 °C, H 30, HI 26.7 °C, WBGT 26 °C, SET 25.6 °C. The third cluster is the criteria with the medium level thresholds (C-M), including the fixed air temperature threshold of 28 °C, adaptive temperature threshold of BS EN Cat I, SSI 32.8 °C, and DI 24 °C. The fourth cluster is the criteria with the high-level thresholds (C-H) which is the greatest number of criteria in comparison to the other clusters, which includes the adaptive temperature threshold of BS EN Cat. II and Cat. III, SSI 37.8 °C, H 35, HI 32.2 °C, WBGT 29 °C, SET 30.0 °C. The fifth cluster and the sixth cluster are combined to be the cluster of criteria with extra-high-level thresholds (C-XH), including the fixed air temperature threshold of 32 °C, H 40, DI 27 °C and WBGT 32 °C. By comparing the percentage of overheating hours in the different clusters Fig. 259.7a, a general equivalency between the different criteria can be summarized in Fig. 259.7b. To better describe the overheating condition in a room, criteria from the 3 groups representing 3 levels of overheating risk: C-L, C-M and C-H, are suggested. The criteria in C-L and C-M may have better performance in estimating the average thermal conditions, while at least one criterion in the C-H group should be selected to evaluate the extremely hot conditions.

259.4 Conclusions

The measured data from the eight buildings show a similar result to the site visit. The school buildings with a night ventilation system have less overheating than the other schools without mechanical ventilation. The overheating in hospitals can be quite different in different rooms due to the operation of air conditioners are quite different in the rooms. In general, the rooms on the top floor without air conditions tend to have severe overheating. The measured data exhibited strong evidence of overheating in existing building stocks in Montreal, showing the necessity for further investigation to mitigate the overheating. The overheating criteria with different types of thermal index are then compared and clustered through a correlation clustering process. Even though there are differences among the criteria, those of similar levels can still achieve a strong concordance for the evaluation of 33 rooms. Overheating criteria at different levels should be used together for a comprehensive assessment of the thermal condition and at least one criterion should be used in group C-H, which includes BS EN Cat. II and Cat. III, SSI 37.8 °C, H 35, HI 32.2 °C, WBGT 29 °C, and SET 30.0 °C.

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