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A systematic evaluation of indoor overheating interactions with outdoor heat conditions

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SUMMARY
Overheating in buildings has been a major health concern for vulnerable occupants during extreme heatwaves. Even though indoor overheating is highly dependent on outdoor climate, it may also be affected by other factors including building envelope characteristics, HVAC operation and internal heat gains. This study is to investigate the synchronisation of indoor overheating with outdoor heatwave. Archetype residential buildings were created and used to conduct EnergyPlus simulations of 31 years climate data of three major Canadian cities. A heatwave evaluation method developed by National Research Council of Canada was used to define heat events and extreme summer weather years. The method uses the transient standard effective temperature (t-SET) to rank heat events in terms of duration, intensity and severity. The results show that in most building configurations, outdoor extreme heatwaves are synchronised with indoor extreme overheating events. Outdoor-based extreme summer weather years are therefore suitable to study indoor overheating risks.

KEYWORDS
Building simulation, Overheating, Heatwave, Extreme weather data, Thermal comfort

1 INTRODUCTION

Overheating problem in buildings has been a significant health concern during extreme heat events and seems becoming more frequent as a result of climate change (Chang et al. 2020). Overheating is found in free-running buildings, buildings with intermittent use or limited capacity of air-conditioning, or fully air-conditioned buildings during HVAC failures or blackouts. Indoor overheating is not solely dependent on outdoor climate, but also on building characteristics and operation, internal heat gains, and occupant behaviour. However, it is not clear whether indoor extreme overheating events are synchronized with extreme outdoor heatwaves. The National Research Council (NRC) of Canada has recently proposed a method to define outdoor heatwaves, patterns and reference extreme summer weather years based on the transient standard effective temperature (t-SET) metric (Laouadi et al., 2020). In this study, the NRC method is applied to indoor overheating events with some modifications to the threshold values of t-SET for daytime and nighttime exposures. The goal is to compare the extreme heat events for outdoor and indoor environments.

2 MATERIALS AND METHODS

Definition of heat events

Heat may affect thermal comfort and health of human subjects. Heat stress indices that are based on a complete heat balance of human subjects are more suitable to study the effect of heat events on subject comfort and health. In this study, the Standard Effective Temperature (SET) index is used for this purpose. SET is the temperature of an environment with 50% relative humidity (RH), mean radiant temperature equal to air temperature and airspeed < 0.1 m/s, in which the total heat loss from the skin of a dummy subject at the actual exertion condition and with a standard clothing insulation (0.6 clo for one met) is the same as that from a subject in the actual environment with actual clothing and activity level (ASHRAE, 2017). The SET is modified to take into account the transient nature of heat events and activity levels during daytime and nighttime exposure, and thus is named Transient Standard Effective Temperature (t-SET) (Laouadi et al., 2020). The magnitude of a heat event of the given duration (Δt) is defined as follows:

$$SETH = \sum_t (t\text{-}SET - t\text{-}SET_r) \cdot \Delta t \quad (1)$$

Where SETH (°C·h) is the magnitude of the heat event (zero if negative), Δt is the calculation time step (h), and $t\text{-}SET_r$ is the reference value of $t\text{-}SET$ above the comfort level, which triggers a physiological response to cool a subject body and a subject action to restore the thermal comfort. The reference value of $t\text{-}SET$ is fixed at 30°C (corresponding to the initiation of sweating or slight warm sensation) for un-acclimatized people and 31.2°C for acclimatised people (Laouadi et al., 2020) during daytime exposure. During night time, the reference value of $t\text{-}SET$ is set to be equal to the lower temperature limit of the adaptive thermal comfort range for the location under consideration or fixed at 26°C (the upper limit value of thermal comfort) for subjects under outdoor or indoor environment exposure, respectively.

A countable (or "meaningful") heat event is declared if its daytime magnitude ($SETH_d$) is higher than a minimum value ($SETH_{d,min}$). In this study, this minimum value is fixed at $SETH_{d,min} = 4°\text{C} \cdot \text{h}$ corresponding to a body water loss lower than 1.2% when a subject is exposed to thermal conditions of one degree SET above the reference value of $t\text{-}SET_{daytime}$ (exposure time of four hours). A heatwave is defined as continuous countable heat events occurring over at least two days. To define exterior heatwaves, $t\text{-}SET$ is calculated considering air temperature, relative humidity, mean radiant temperature (MRT), wind speed and solar radiation of the outdoor climate, and a subject is assumed walking outdoors during daytime and sleeping during night time. To define an indoor overheating event, $t\text{-}SET$ is calculated considering indoor air temperature, relative humidity, mean radiant temperature (MRT) and airspeed, and a subject is assumed seating quietly indoors during daytime and sleeping during night time. An overheating event is then defined as continuous meaningful heat event occurring over at least two days. Heatwaves and overheating events both could be characterised by three features: duration, intensity, and severity. The duration D (days) is measured in terms of the number of days of sustained heat events. The severity (denoted by SETH) is calculated as the summation of magnitudes of daily heat events:

$$SETH = \sum_{days} \sum_t (t\text{-}SET - t\text{-}SET_r) \cdot \Delta t \quad (2)$$

Where SETH (°C·h) is the severity of a heatwave or overheating event of a duration of two or more days. The intensity I (°C) is calculated as the ratio of severity to duration (expressed in hours):

$$I = \frac{SETH}{24 \cdot D} \tag{3}$$

Accordingly, one can distinguish three major types of heatwaves or overheating events, namely: long, intense and severe or a combination of long and intense, long and severe, or severe and intense.

Building models and configurations

Natural Resources Canada (NRCan) has generated archetype models of residential buildings (Parekh, 2012). 500,000 houses were rated across Canada to understand the characteristics of existing and new houses for predicting the effects of construction changes. Among those houses, there were 438,746 single-detached houses. According to the archetype characteristics, we have created two archetype models for the single-detached house and row house to study space overheating using the EnergyPlus software (v9.2; DOE, 2020). Each house model has two floors above ground, attic space and a full basement, as shown in Figure 1. The first floor is assigned to living room where occupants spend their time during daytime and the second floor is assigned to bedrooms where occupants sleep at night. The house construction characteristics are summarised in Table 1. The single-detached house has windows on each facade of the first and second floors, whereas the row house has windows on the south and north (or east and west) facades. Internal heat gains from occupancy, lights and equipment are taken from the National Building Code of Canada (NRC, 2015): 3 people per house, lighting gains =5 W/m^2 of the heated area; and equipment gains = 5 W/m^2.

A B

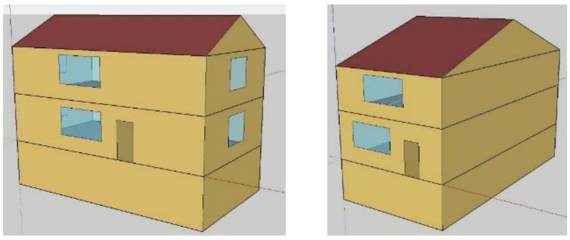

Figure 1. The geometry of building models: a) single-detached house and b) row house

Table 1. Building properties of the archetypes - baseline buildings

Property	Single-detached house		Row house	
	Old Construction	New Construction	Old Construction	New Construction
Orientation of windows	N-S-E-W	N-S-E-W	N-S (or E-W)	N-S (or E-W)
Heated area (m^2)	160.20	160.20	220.70	220.70
Window/Wall ratio (%)	15.27	15.27	23.95	23.95
Exterior Wall Effective R (m^2 KW^{-1})	1.80	3.20	1.80	3.20
Attic insulation Effective R (m^2 KW^{-1})	3.60	8.20	3.60	8.20
Window (wooden frame) U-Value (W m^{-2} K^{-1})	2.58	1.58	2.58	1.58
Window SHGC	0.702	0.67	0.702	0.67
Design Infiltration Rate (ACH)	6.86	2.32	9.32	2.80

To investigate the impact of different passive measures in buildings on the indoor overheating condition, we have applied six different configurations to both old and current constructions. Three primary passive measures are considered, including interior blinds, exterior shades and natural ventilation through windows. Interior blinds are opened by setting the slat angle as vertical (slat angle 90°) and closed by setting the angle at 175° (almost horizontal). Exterior shades are always closed with 5% solar transmittance. The above three configurations could be combined with or without natural ventilation. Natural ventilation is realised through opening windows for 25% when the indoor temperature exceeds the setpoint 26°C and the outdoor temperature. Using the above set of parameters, 1920 simulations (2 constructions, two orientations for the row house, six configurations, 31 historical weather files and one typical meteorological year (TMY) weather file, and three cities including Ottawa, Toronto, and Montreal) have been conducted.

Selection and comparison of extreme years

Thirty-one years (1986-2016) of historical climate data have been used in the simulations to capture all types of outdoor heatwaves and indoor overheating events. The climate data were generated for selected Canadian cities using the methodology of Gaur et al. (2019). The summer period is fixed from May to September. Heatwaves and overheating events for each year are identified and sorted by maximum duration, intensity, and severity. The maximum values are assigned to each year. For each simulation case, the top two extreme years among 31 years are listed and compared in terms of heatwaves and overheating events. The software CumFreq (Oosterbaan, 2019) is used to extract the extreme years that have a return period of 15.5 years (second rank out of 31 years). The synchronisation of extreme overheating events with heatwaves is accepted if both are in the first two ranks.

3 RESULTS AND DISCUSSION

Comparison of indoor and outdoor-based extreme years

Table 2 lists the first two extreme years of heatwaves and overheating events for the single-detached house with old and current constructions in Ottawa, Ontario, Canada. The duration, intensity and severity of heatwaves and overheating events are also shown in the table. Outdoor-based extreme years that have a return period closest to 15.5 years (calculated using CumFreq software) are coloured in red. The extreme year 2010 is selected as the representative year for Ottawa that could be considered as the reference summer weather year (RSWY) (Laouadi et al., 2020) since it combines two features of heat waves - long and severe . The year 2010 also ranks in the top two indoor-based extreme years for all house configurations (coloured in red). Similarly, the extreme years of 2006 and 2010 for Toronto and Montreal (not presented here) rank in the top two overheating extreme years for 75% and 58% of house configurations, respectively. For a row house with North-South and East-West orientations in Ottawa, 2010 ranks in the top two overheating extreme years for 80% and 78% of house configurations, respectively. Overall, for most building configurations, exterior heatwaves also result in extreme interior overheating events. Therefore, under cold climates of Canada, outdoor-based extreme summer weather years are suitable for assessing overheating risk in free-running buildings. However, further testings of the NRC model for generating extreme summer years that are independent of buildings are needed to assess their suitability for other climates such as warm, hot, hot and humid or tropical climates where heatwaves may be present all year long.

Table 2. Top two extreme years of exterior heatwave and interior overheating events for the single-detached house in Ottawa, Ontario, Canada. Bolded years are outdoor-based extreme

years with return periods closest to 15.5 years. Representative years are selected when they combine at least two features of heat events.

	Year	Duration	Year	Intensity	Year	Severity	Rep Year
Exterior	**2010**	7	2002	3.83	**2010**	437	**2010**
	1987	7	**2006**	2.89	1987	415	
Case1: Single-detached house with old constructions							
Configuration	**Year**	**Duration**	**Year**	**Intensity**	**Year**	**Severity**	**Rep Year**
Closed windows + open internal blinds	2005	23	2002	4.82	2005	1922	2005
	2003	17	1987	4.67	**2010**	1613	
Closed windows + closed internal blinds	2003	15	**2006**	5.11	**2010**	1251	**2010**
	2010	14	2002	4.52	2005	1153	
Open windows + open internal blinds	**2010**	4	2002	2.42	**2010**	224	**2010**
	1988	4	**2010**	2.33	2002	175	2002
Open windows + closed internal blinds	**2010**	4	**2010**	2.13	**2010**	204	**2010**
	2002	3	2002	2.13	2002	154	2002
Closed windows + closed external shading	2013	5	2002	4.47	**2010**	414	**2010**
	2006	5	**2010**	4.31	2013	400	2013
Open windows + closed external shading	**2010**	3	**2010**	2.27	**2010**	164	**2010**
	2002	3	2002	1.98	2002	143	2002
Case2: Single-detached house with current constructions							
Configuration	**Year**	**Duration**	**Year**	**Intensity**	**Year**	**Severity**	**Rep Year**
Closed windows + open internal blinds	1987	62	2005	7.71	1987	7890	1987
	1988	50	**2010**	7.40	1988	7737	1988
Closed windows + closed internal blinds	1989	47	2005	6.94	1988	6469	1989
	1988	45	**2010**	6.61	1989	6189	1988
Open windows + open internal blinds	**2010**	4	2002	2.60	**2010**	247	**2010**
	1988	4	**2010**	2.58	1988	188	1988
Open windows + closed internal blinds	**2010**	4	**2010**	228.00	**2010**	228	**2010**
	2002	3	2002	171.31	2002	171	2002
Closed windows + closed external shading	**2010**	14	2002	5.92	**2010**	1625	**2010**
	2003	13	1994	5.19	2005	1380	
Open windows + closed external shading	**2010**	4	**2010**	2.15	**2010**	207	**2010**
	2002	3	2002	2.09	2002	151	2002

Indoor heat stress levels during exterior heat waves

As mentioned above, there are three types of heatwaves and overheating events: long, severe and intense. According to the cumulative frequency analysis for Ottawa, 2010 (Jul. 5-10) and 2006 (Jul. 31- Aug. 03) are selected as the extreme years with long/severe and intense heat waves, respectively (Laouadi et al., 2020). Figure 2 shows the indoor temperature and t-SET of single-detached house and row house (N-S) with old construction, closed interior blinds and without natural ventilation. As shown in Figure 2 (A1) (B1), the difference between indoor and outdoor temperature is more significant during night time than during daytime. As shown in Figure 2 (A2) (B2), during the long/severe and intense heatwaves, the t-SET in both single-detached house and row house (N-S) is higher than 26°C for at least two days during night for several hours, which would disturb sleeping, and higher than 31.2°C when occupants are assumed awake (7:00 am to 10:00 pm). The t-SET is above 34.5°C for several hours during the daytime of the whole heatwave, in which condition the thermal sensation is very uncomfortable and the people’s physiological state is profuse sweating according to Parson (2003); the t-SET is even up to above 37.5°C for several hours, which indicates people would feel very uncomfortable, and might lead to failure of thermoregulation.

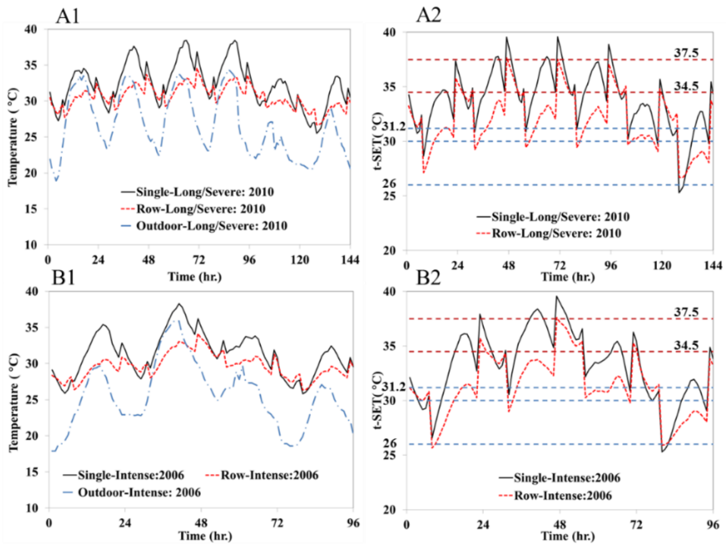

Figure 2. Comparison of outdoor temperature, indoor temperature and t-SET

4 CONCLUSIONS

For most typical configurations of free-running residential buildings, indoor extreme overheating events are synchronized with extreme outdoor heatwaves. Outdoor-based extreme summer weather years as developed by NRC (Laouadi et al., 2020) are therefore suitable to assess overheating risk in buildings. The results for the indoor temperatures and t-SET during the periods of heatwaves showed that building occupants would be under extreme heat stress (excessive sweating during daytime; t-SET > 34.5°C) and their sleep would be disturbed during night time (t-SET> 26°C). Sleep disturbance weakens the physiological response of occupants in the next hot days, which may consequently affect the health of vulnerable occupants.

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