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Climate Resilience Buildings:

Guideline for management of overheating risk in residential buildings

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Guideline for management of overheating risk in residential buildings

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DISCLAIMER

This guideline document, the first of a series of guideline to be published related to the overheating of buildings from the effects of climate change, was developed through completion of several research projects under the Climate Resilience Buildings and Core Public Infrastructures Initiative. The contents of this guideline were based on the best knowledge available at the time of publication and new research related to heat stress and thermal comfort for both young and elderly people occupying workplaces and home environments. Building simulation was used to analyze overheating risk in archetypical residential buildings that conformed to the local construction practices in Ottawa (Ontario). The National Research Council Canada and the authors of this publication shall bear no responsibility nor liability whatsoever, or be indemnified for any kind of harm, loss or personal injury resulting from the use of this guideline.

INTRODUCTION

In cold climates having temperate summers, over the past decades overheating has not been an issue in respect to older and leakier buildings. However, with the ever-increasing threat of global warming and aggressive measures to reduce winter heating energy use to improve the energy efficiency of homes, overheating has become a real concern to the comfort and health of building occupants. Overheating is the result of excessive heat accumulation in building interiors combined with limited means to effectively dissipate this heat to the outdoor. The outdoor environment is the principle cause for this excessive heat, particularly during extreme heat events as occur in the summertime. However, buildings can exacerbate the situation by generating additional internal heat from equipment, lighting, occupants (density) and as well, from the trapping of heat given high levels of insulation, more effective airtightness of envelopes and inadequate space ventilation.

The topic of overheating in buildings is still under intensive research in many countries around the world. Overheating should not be confused with thermal discomfort, which is a mature topic in air-conditioned or naturally ventilated buildings. The fundamental difference between the two is that thermal discomfort is an instant feeling of building occupants expressing dissatisfaction with their environmental conditions. Overheating, however, expresses the cumulative effect over continuous days of environmental conditions related to both comfort and the health of occupants. Furthermore, thermal comfort (or discomfort), relates to the occupied spaces whereas overheating relates to the occupants themselves, and who may change spaces when conducting different activities or also adapt to heat stress. From this viewpoint, and within this guideline document on overheating in buildings, a new approach is introduced for evaluating overheating from the perspective of heat-related health outcomes as may arise from body dehydration and increased body core temperature prior to any occurrence of heat related illnesses.

This guideline document consists of thirteen chapters in which important information is provided on the relationships between heat and human body response, a general framework to evaluate overheating risk in buildings and application of the framework to Canadian residential buildings. The first chapters (1 to 3) present the purpose, scope and definitions of terms used in this document. Chapter 4 presents pertinent information on the effects of heat on human health and the manner in which the human body responds to heat through thermoregulation and adaptation to heat. Heat related illnesses corresponding to different levels of failure of thermoregulation processes are presented with key prevention measures. Chapter 5 presents new research-based information on thermal comfort and thermal stress. The chapter includes improvements to the currently available thermal comfort and heat stress indices to overcome their limitations when covering broad ranges of input parameters to predict thermal comfort requirements for young and older people (> 65 year old) in workplaces and sleeping environments. Heat stress levels in terms of core and skin temperatures, dry and evaporating skin heat losses, and body water loss for young and older people are presented under typical indoor environmental conditions. Chapters 6 to 9 present a general framework to evaluate overheating risk in buildings. Chapter 6 includes a new approach to define and characterise overheating events and the criteria to declare overheating in buildings with young or older occupants. Chapter 7 lists the factors that can increase overheating risk in buildings. Chapter 8 presents the outdoor environment as the primary factor influencing overheating. The chapter includes new approaches to collect long term climate data for the historical period and future climate projections covering seven global warming scenarios until the end of the 21st century and define and characterise climatic extreme heat events. A procedure to extract summer weather years with various types of extreme heat events from the long term climate data is presented for application to any local climate. Spatial exposure maps of extreme heat waves over selected Canadian locations are presented for the historical period and future climate projections. Chapter 10 lists potential mitigation measures to reduce overheating risk in buildings. Chapters 11 to 13 present the results of overheating by applying the framework of Chapters 6 to 9 to three types of residential buildings (detached and attached homes and mid-rise multi-unit residential buildings) under the current climate and seven scenarios of future climate projections.

WHO SHOULD USE THE GUIDELINE

This guideline document provides a wealth of information to manage the risk to overheating in residential buildings located in typical cold climates having temperate summers, as are found in Canada, and their future climate projections. It is intended to inform building developers, designers (architects), modellers and simulators, and HVAC engineers having interest in the design and retrofit of high performance and climate resilient buildings. This guideline as well provides research-based information on technical requirements and means of evaluation that are intended to help ensure the comfort and safety of building occupants deemed vulnerable to overheating, such as the elderly, that would be useful to building energy code officials to permit incorporating overheating in building energy codes and building energy efficiency standards.

1 PURPOSE

The purpose of this guideline is two-fold: (i) To provide a framework to evaluate overheating risk in buildings through the use of building simulation or continuous field monitoring of building interior conditions; (ii) To apply the framework to assess suitability of selected mitigation measures to reduce overheating risk in archetypical old, retrofitted, new and net zero energy residential buildings under the local current climate of Ottawa (Ontario) and future climate projections.

2 SCOPE

This guideline is intended to address the evaluation of overheating risk in buildings arising from extreme heat events of local climates at building sites. However, this initial guideline contains overeating risk data for residential buildings as obtained by applying the presented framework on overheating evaluation for the city of Ottawa (Ontario) as a means of assessing the selected overheating mitigation measures.

Local climate data has been extracted from the most recent historical climate observations over the past three decades. The future climate projection data for various climate change scenarios are, however, extracted from the raw climate modelling databases of Environment and Climate Change Canada (ECCC). The raw climate data were bias-corrected for the location under study, but they still carry biases when compared with the historical climate observation data. Therefore, overheating risk data obtained for future climate projections should be used for relative comparison purposes and are not intended to be used as absolute values. Furthermore, local climate modifiers such as the urban heat island effects are not accounted for in the local climate data and future climate projections.

There are many comfort-related definitions of overheating as used by various organisations and researchers around the world. The guideline of this document adopts, however, a newly developed definition of overheating as it relates to the comfort and heat-related health effects of average-age adults or older building occupants who are in good health conditions. Building occupants are assumed capable of tolerating a slight level of thermal discomfort without any adverse health effects, and where they can adapt to restore thermal comfort by simple means such as changing clothing, using portable fans, opening windows, moving from a warm to a cooler space, or other such measures of adaptation. Children (under 15 years old) or adult occupants with prior health conditions are not considered in this document; only the older and the young adults.

Finally, these guideline apply to residential buildings of single detached and row houses and mid-rise multi-unit residential buildings that follow typical Canadian construction practice in 1980s (old), current National Building Code of Canada (NRC,2015) and future net zero energy design (30% increase in thermal performance).

3 DEFINITIONS

Special terms used in this guideline document are defined as below.

Adaptive thermal comfort	Thermal comfort in non-air conditioned built environments where occupants are given opportunities to adapt to heat or cold conditions
Daily indoor heat event	An indoor heat event with warm temperatures that occurs daily over at least a prescribed number of hours during daytime and triggers a physiological response and action of building occupants to restore thermal comfort
Daily outdoor heat event	An outdoor heat event with warm temperatures that occurs daily over at least a prescribed number of hours during daytime and triggers a physiological response and action of people under its direct exposure in sunshade to restore thermal comfort
Heat wave event	Synonymous of outdoor extreme heat event
Heat wave, duration (days)	Number of continuous daily outdoor heat events
Heat wave, intensity (°C)	Equal to severity / (duration * 24)
Heat wave, severity (°C*h)	Magnitude of a heat wave event given by Equation (1) and evaluated under outdoor conditions
Older building occupant	Adult occupants with age over 65 years.
Outdoor extreme heat event	Continuous daily outdoor heat events that affect the outdoor comfort of people exposed to such heat events in sunshade over at least one day
Overheating event	Continuous daily indoor heat events
Overheating	The cumulative effect on the thermal comfort (or heat stress) and health of occupants directly exposed to continuous daily indoor heat events
Overheating, duration (days)	Number of continuous daily indoor heat events
Overheating, intensity (°C)	Equal to severity / (duration * 24)
Overheating, severity (°C*h)	Magnitude of an overheating event given by Equation (1) and evaluated under indoor conditions
Standard effective temperature (SET), (°C)	Steady state temperature of still air of an imaginary indoor environment at 50% relative humidity and mean radiant temperature equals to the air temperature, in which an imaginary person performing the same actual activity and wearing clothing standardized for the activity level has the same skin heat loss, thermal stress (skin

	temperature) and thermal strain (skin wettedness) as the actual person in the actual environment (Parsons, 2014).
Thermal (heat or cold) stress	Changes in human body (core and skin) temperatures and cardiac output (blood volume) due to the imposed environmental conditions and person activity, potentially leading to thermal discomfort, health problems, organ injuries, or death.
Thermal comfort	The condition of mind that expresses satisfaction with the thermal environment (ASHRAE, 2017)
Transient standard effective temperature (t-SET), (°C)	Value of SET evaluated at each time step
Young building occupant	Adult occupants with average-age of 35 years old

4 EFFECTS OF HEAT ON THE HUMAN HEALTH

It is well established that heat exposure can lead to illnesses and injuries or damage of human body tissues (Yeo, 2004; HC, 2011; Parsons, 2014; EPA, 2016). The human body maintains an optimum body core temperature of 37°C to perform its vital physiological functions. The environmental thermal conditions imposed on the human body combined with its activity level will affect the body temperature, and will therefore trigger a thermoregulatory response to cool the body by balancing the heat gains with the heat loss. If the thermoregulatory system is overwhelmed by the imposed thermal conditions, the human body will experience some minor to serious illnesses depending on the thermal stress level. Heat-related illnesses develop when the body core temperature is between 37°C and 40.6°C, and tissue injury or destruction occurs at higher body core temperatures (Yeo, 2004).

4.1 Body response to heat

The physiological system of the human body continuously generates metabolic heat to maintain a body core temperature within a very tight range of 35°C to 41°C around a neutral value of 37°C (Periard et al., 2015). The excess heat is dissipated to the environment through respiration, and peripheral blood flow to the skin. The skin surface exchanges the blood-transported heat with the environment though radiation, convection and sweat evaporation. If the body core temperature is above the neutral value, the thermoregulatory system uses two mechanisms to dissipate heat and cool the body: (1) it increases the peripheral blood flow by increasing the cardiac output (heart blood flow) and vasodilation of the blood vessels in the skin layer; and (2) it releases sweat (water and salt) at the skin surface for evaporative cooling. The first cooling mechanism is triggered when the environmental thermal conditions are close to the neutral conditions (slightly warm on the thermal comfort scale) and the body core temperature is between 36.8°C to 37.2°C (Rida et al., 2014). The second cooling mechanism is the most efficient one; it is triggered when the first cooling mechanism is not sufficient under higher body core temperatures. However, this cooling mechanism may be compromised by high values of ambient relative humidity and body dehydration status. In hot and dry conditions, heat can easily be removed from the body by sweat evaporative cooling until reaching the maximum sweat rate of the sweat glands. Body water loss by sweating should be replaced by fluid and electrolytes intake to avoid dehydration. If the body dehydration occurs, the muscle blood flow, sweat rate and salt retention may decrease accordingly, resulting in higher core temperatures and consequent development of health issues. In hot and humid conditions, the sweat evaporative cooling may be significantly reduced, and the body will therefore accumulate heat, and the high peripheral blood flow to the skin may compromise the blood and nutrient flows to other body vital organs, potentially resulting in heat-related illnesses or injuries (HC, 2011). Table 1 shows the core temperature levels and its associated heath conditions.

Table 1. Core temperature and associated heath conditions (Pisacane et al., 2007)

Core temperature (°C)	Health condition
> 44	Brain death certain
41 – 44	Heat stroke
39 – 41	Heat exhaustion
38 - 39	Heat cramps; Heat syncope
36 - 38	Normal
35 - 36	Mild hypothermia with mild to severe shivering
34 - 35	Moderate hypothermia with intense shivering
32 - 34	Severe hypothermia with violent shivering
30 - 32	Severe hypothermia with no shivering
28 - 30	Severe hypothermia with possible heart fibrillation
26 - 28	Severe hypothermia with possible death
< 26	Death certain

4.2 Adaptation to heat

A person's ability to adapt to heat is an important natural defence to mitigate heat-related health illnesses. Under natural environmental conditions, people adapt to restore thermal comfort if they experience thermal discomfort by using various means of adaptation, that can be grouped as physiological (or heat acclimatization), behavioural, and psychological (Parsons, 2014).

Heat acclimatisation refers to the physiological adaptation in response to repeated exposures to a hot environment over a few weeks duration (HC, 2011; ISO, 2017), thus increasing the ability of people to become more tolerant to temperatures higher than the neutral conditions (Parsons, 2014). Acclimatization involves various physiological changes, including decreasing the threshold body core temperature for sweating and blood flow (thus sweating initiated earlier), increased dilute sweat production, lower peripheral blood flow and salt conservation. Acclimatisation explains why people in warm climates tolerate higher threshold temperatures than people in cold climates (Hajat and Kosatky, 2010; Basu, 2009). Furthermore, extreme heat events (EHE) have higher impacts on the population in early summer as compared to full summer due to fewer people being acclimatized at the beginning of the warm season (Basu, 2009; HC, 2012).

Behavioural (or physical) adaptation is the most effective means to ensure survival, comfort and performance (Parsons, 2014). It involves any changes that a person can make to oneself or the environment to reduce the effect of heat. Personal and environmental changes may include wearing lighter clothes, use of air conditioning, use of ventilation (portable or ceiling) fans, opening windows, moving around to avoid direct heat, and other similar measures. Behavioural adaptation is the key driver to achieve adaptive thermal comfort in naturally ventilated buildings (Brager and de Dear, 1998).

Psychological adaptation refers to the altered perception of and reaction to sensory information due to past experience and expectations (Parsons, 2014). In other words, people may perceive and react differently to the imposed environment conditions, and their physiological and behavioural adaptation may therefore be influenced accordingly. Psychological adaptation plays a significant role in naturally ventilated buildings where occupants are more tolerant to heat than in air conditioned buildings (Brager and de Dear, 1998).

4.3 Heat related illnesses

Heat related illnesses progress from the start of feeling thermal discomfort, to mild heat stress, or syncope or cramps, thereafter to heat exhaustion, and afterward to heat stroke, potentially leading to organ dysfunctions (such as renal failure) and, in some instances, death. Heat illnesses are caused by body dehydration, electrolyte (salt) losses, and failure of the thermoregulatory system (Yeo, 2004).

Heat syncope (i.e. fainting) is a transient loss of consciousness resulting from a reduction of cerebral blood flow, preceded frequently by pallor, blurring of vision, dizziness and nausea. It may occur in persons suffering from heat stress. Mild dehydration, which develops in most persons exposed to heat, contributes to the probability of heat syncope. Individuals who suffer from cardiovascular diseases or who are un-acclimatized to heat are predisposed to heat syncope or collapse. The victims usually recover consciousness rapidly after they are laid flat (Ogawa, 2021).

Heat cramps (mild heat stress) are caused by the loss of fluids and salts due to prolonged heavy sweating. It is accompanied by painful muscle cramps and spasms while body temperature hardly rises. Cessation of activity, drinking plenty of water and application of a firm pressure on cramping muscle or gentle message may relief the symptoms (EPA, 2006).

Heat exhaustion occurs when the body core temperature is between 37°C and 40°C, and the body becomes dehydrated and can no longer dissipate heat. The cardiovascular system is unable to meet the needs for cooling of skin surface and muscles due to lower blood volume. It is accompanied by heavy sweating, fatigue and weakness, dizziness and fainting, and nausea and vomiting (Yeo, 2004; EPA, 2006; HC, 2011). Drinking water with electrolytes and cooling the body may relief the symptoms (EPA, 2006). If heat exhaustion is left untreated it will progress to a heat stroke.

Heat stroke occurs when the thermoregulatory system fails, the body core temperature is higher than 40.6°C (extreme hyperthermia), and the skin becomes hot and dry. The symptoms include headache, confusion, nausea and dizziness. Heat stroke is a severe medical emergency that requires prompt diagnosis and rapid and aggressive treatment to avoid death (Yeo, 2004; EPA, 2006). If it occurs, the body needs immediate cooling (e.g., placing individual in air conditioned area), and taking measures for a medical emergency.

4.4 Prevention of heat related illnesses

Prevention measures to avoid the occurrences of any heat-related illnesses are those that can minimise body dehydration and prevent increases in the core temperature. Those may include:

- Get acclimatized to heat to increase the tolerance to warm or hot temperatures. Acclimatization to heat can be induced through gradual exposure in a warm environment in late of spring or beginning of summer for several weeks. Maintenance of full heat acclimatization requires exposure to heat three to four times per week (Nunneley, 2021);
- Reduce the activity level in environments with warm or hot temperatures and high humidity;
- Continuously hydrate the body by drinking sufficient fluids and electrolytes comparable to the degree of sweating. Sweating in the order of 1 to 2 litres/h is common in average-age adults. It is advisable for an individual not wait to drink water as a person's thirst may also show up after losing a significant amount of body water up to 2 litres (Nunneley, 2021);
- Wear clothing that is appropriate to the environment and heat conditions. Clothes that are too thick and not highly permeable to air and moisture will reduce body heat loss and can consequently increase the body temperature. If a person feels too hot, his excess clothing ought to be removed until he regains a sense of acceptable environment conditions.

4.5 People vulnerable to heat

People vulnerable to heat are a category of population who are more susceptible to heat stress, or have reduced mobility and economic ability to adapt to or mitigate the effects of heat in the environment to which they are exposed (IOM, 2011). They include:

Older people – Older people are commonly defined as those whose age is above 65 years. In Canada, older people make up about 17% of the total population (Table 2). Due to age-related physiological changes, older people are the most affected by extreme heat exposure (HC, 2011; Astrom et al., 2011). Compared to healthy younger adults, older people have a reduced ability to acclimatize to heat and are less sensitive to heat and thirst. In other words, they have lower sweating rate, blood flow to the skin and body extremities, cardiac output (blood volume), vasodilation of blood vessels, and metabolic rate; and have a higher temperature threshold for sweating, and body fat percentage (Van Hoof et al., 2017; Roelofsen, 2017). As a consequence, older people may accumulate heat, resulting in higher body core temperature and lower skin temperature in their extremities, thus putting them under higher risk of hyperthermia (Rida, 2014; Ma et al., 2017). Studies found that older people prefer warmer (+2°C) environments than younger adults to compensate for their lower metabolic rate and reduced peripheral blood flow (Van Hoof et al., 2017; Schellen et al., 2010; Parsons, 2014). Older people may also have less capacity and mobility to behaviourally adapt to the environmental conditions.

Children — Infants and children (< 15 years of age) make up about 17% of the total Canadian population (Table 2). They are the second category of population vulnerable to extreme heat exposure (Basu, 2009; Song, 2017). The thermoregulatory system of children is not fully developed as compared to adults. Furthermore, children have reduced sweating ability. Children tend to have higher body and skin temperatures due to their higher activity level (metabolic rate) and surface area to body mass ratio, putting them at a higher risk of hyperthermia during exposure to extreme heat (HC, 2011). Furthermore, infants and young children are reliant on caregivers to make any adaptation (e.g., dressing, drinking water, and opening windows) to themselves or surrounding environment to reduce the risk of extreme heat exposure.

Sick people — The impact of exposure to extreme heat on people's health is further exacerbated for those having prior health issues and those who take medication that interferes with the thermoregulatory system (e.g., use of aspirin and psychotropic drugs) or the retention of salt and water. Typical sicknesses include chronic illnesses, cardiovascular diseases, respiratory diseases, diabetes, obesity, hypertension, cancer, kidney diseases, pneumonia, malnutrition, as well as other illnesses (HC, 2011; Lavigne et al., 2014; IOM, 2011).

People with low social-economic status (SES) — This group includes socially and materially-deprived people of low-income, low education, or the physically impaired, having reduced access to transportation, and no access to air conditioning; this also includes socially isolated people such as the homeless, those living alone, and those with limited social interactions. The SES factor was an evident mortality cause in the 1995 Chicago (Kaiser et al., 2007) and 2003 European heat wave events (Robine et al., 2008).

Physically active people — This includes healthy people who are engaged in outdoor activities such as outdoor workers, athletes, tourists, and other active people. Their high activity level (high metabolic rate) constitutes a risk factor under extreme heat exposure as it compromises the blood flow through the muscles with that needed for skin surface cooling.

Table 2. Distribution of Canadian population – 2016 census data (Source: StatCan, 2016)

Province and City	Total	%(*)	0 - 14 yrs	%	≥ 65 yrs	%
Canada	35,151,730		5,839,570	**17**	5,935,635	**17**
Newfoundland & Labrador	519,715	1	74,440	0.2	101,025	0.3
St John's	205,955	40	32,460	6	30,555	6
Prince Edward Island	142,905	0.4	22,685	0.1	27,715	0.1
Charlottetown	69,325	49	11,320	8	12,130	8
Nova Scotia	923,600	3	133,830	0.4	183,820	1
Halifax	403,390	44	60,535	7	63,170	7
New Brunswick	747,100	2	110,495	0.3	148,785	0.4
Moncton	144,805	19	22,720	3	25,120	3
Quebec	8,164,360	23	1,333,255	4	1,495,190	4
Montreal	4,098,925	50	691,350	8	671,690	8
Ontario	13,448,495	38	2,207,975	6	2,251,655	6
Ottawa	991,725	7	165,975	1	152,850	1
Toronto	5,928,040	44	985,615	7	858,580	6
Manitoba	1,278,365	4	243,825	1	198,965	1
Winnipeg	778,490	61	132,825	10	120,085	9
Saskatchewan	1,098,355	3	215,685	1	170,430	0.5
Saskatoon	295,095	27	55,695	5	37,900	3
Alberta	4,067,175	12	779,155	2	500,220	1
Calgary	1,392,610	34	261,455	6	153,005	4
British Columbia	4,648,055	13	691,385	2	848,990	2
Vancouver	2,463,430	53	362,110	8	387,315	8

(*) Provincial population percentage is calculated relative to the total Canadian population; and city percentage is calculated relative to the total provincial population

5 THERMAL COMFORT AND THERMAL STRESS

Thermal comfort and thermal stress indices are important industry metrics used in occupied spaces for the intent to protect the health of people and to maximize their performance and productivity. Thermal comfort is essentially a psychological phenomenon not directly related to the physical environment and physiological state of people (Parsons, 2014). ASHRAE (2017) defines the thermal comfort as "***the condition of mind that expresses satisfaction with the thermal environment***". ASHRAE developed the thermal sensation scale to relate thermal comfort to the physical environment and physiological state. Thermal sensation indicates how people feel the thermal environment, by relating the sensory information of human body with its physiological response. The thermal sensation scale is made of seven points: Cold (-3), Cool (-2), Slightly cool (-1), Neutral (0), Slightly warm (+1), Warm (+2), and Hot (+3). Thermal sensation accounts for personal factors (i.e., activity level, and clothing insulation) of average age adults and environmental factors (i.e., air temperature, mean radiant temperature, air speed, and relative humidity). It is believed that if thermal comfort is maintained around thermal neutrality, there will be minimum effect on the health of people (Parsons 2014).

Thermal comfort data have been developed for a large group of people of all genders and adults that are in good health based on subjective studies in air conditioned laboratory spaces under steady state heat and cold exposure (Parsons, 2014). After many field studies in real buildings, it was found that the comfort requirement in air-conditioned spaces cannot be applied to un-air-conditioned (free-running) or naturally ventilated buildings. In those buildings, people are more tolerant to warmer or colder temperatures they are adapted to during previous long term exposure. Another stream of thermal comfort indices has thus emerged, specifically, adaptive thermal comfort. The adaptive thermal comfort relates the comfort operative temperature to only the monthly running average temperature of the outdoor environment. Personal and other environmental factors are assumed to be within certain ranges as typically found in the studied buildings.

Thermal comfort data are, however, centered on the comfort range around neutrality and the discomfort range provides only an indication of thermal stress as felt by people but provides no insight on the physiological response in terms of body temperatures and sweating. A third category of indices have been developed from thermal stress studies, which cover the discomfort range with related heat-related health issues.

In this guideline, the two primary indices that have been selected are comfort and thermal stress. The work described in this document shows how these indices have been revised and improved when used to evaluate overheating risk on building occupants during EHEs.

5.1 PMV-PPD indices

Fanger (1970) developed the predicted mean vote (PMV) index based on many subjective studies in controlled laboratory spaces. The PMV index indicates the amount of heat that needs to be added to or subtracted from the metabolic heat to achieve thermal comfort of the whole body. The comfort conditions correspond to the physiological state where the human body is in steady state heat balance with the environment, and the average skin temperature and sweating are within the comfort limits (Parsons, 2014). The PMV index accounts for the six personal and environmental factors, and uses the ASHRAE thermal sensation scale as mentioned before. Fanger (1970) also developed the predicted percentage of dissatisfied (PPD) and linked it to the PMV scale. The PMV neutral thermal conditions (-0.5 to +0.5) correspond to a satisfaction level of 80% (or PPD = 10%). The PMV-PPD indices are the most accepted thermal comfort metrics amongst practitioners and are adopted in many international standards (e.g., ASHRAE 55- 2017; ISO 7730-2005; CSA Z412-17). Recent studies using the ASHRAE Global Thermal Comfort Database II showed, however, that the accuracy of the PMV index is only 34% (meaning that 66% of the cases the PMV index has significant biases compared to the measured or observed thermal sensation votes) (Cheung et al., 2019). The PMV index is only reliable for the comfort range (-0.5 to +0.5) in air-conditioned spaces. Furthermore, PMV is not applicable to the comfort of sleeping persons (ASHRAE, 2017), and older people, particularly in the discomfort ranges.

5.2 Adaptive thermal comfort

The adaptive thermal comfort is applicable to non-air-conditioned (free-running) or naturally ventilated office buildings in locations where the prevailing monthly mean temperature of the outdoor environment varies between 10°C to 33.5°C (ASHRAE, 2017). In those buildings, occupants are assumed in sedentary activities (metabolic rate from 1 to 1.3 met), and are given adaptation opportunities to change their clothing (0.5 to 1 clo), open windows, use ventilation fans, move around, or other measures to adapt to their surroundings. The comfort operative temperatures in those buildings are a few degrees Celsius higher than in air-conditioned buildings.

Figure 1 shows the upper and lower comfort operative temperatures as a function of the monthly average of the outdoor temperature according to ASHRAE 55 (2017); those values are summarized in Table 3 for the month of July, and for selected major Canadian cities.

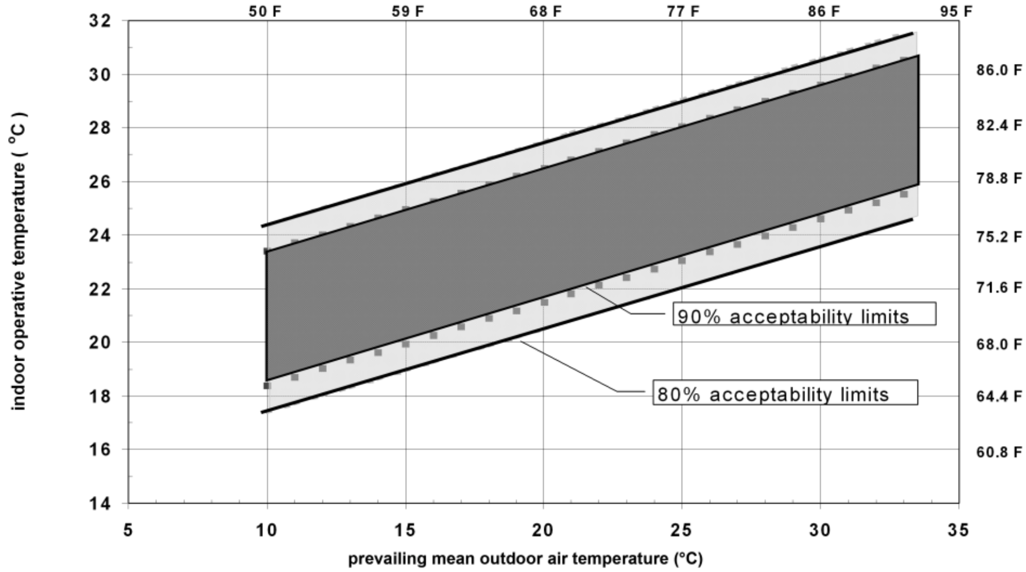


Figure 1. Operative temperature of the adaptive thermal comfort of ASHRAE-55 in naturally ventilated indoor spaces (courtesy of ASHRAE, 2017)

Table 3. ASHRAE-55 (2017) adaptive comfort operative temperatures for selected Canadian cities in July. The monthly averages of the outdoor temperature are taken from the historical climate data of 1981-2010 of ECCC (2018a)

Location	July average outdoor temperature (°C)	ASHRAE-55 Lower operative temperature (°C)	ASHRAE-55 Upper operative temperature (°C)
St John's (NF)	15.5	19.1	26.1
Charlottetown (PEI)	18.7	20.1	27.1
Halifax (NS)	18.8	20.1	27.1
Moncton (NB)	19.5	20.3	27.3
Montreal (QC)	21.2	20.9	27.9
Ottawa (ON)	21.2	20.9	27.9
Toronto (ON)	22.3	21.2	28.2
Winnipeg (MB)	19.7	20.4	27.4
Saskatoon (SK)	18.5	20.0	27.0
Calgary (AB)	16.5	19.4	26.4
Vancouver (BC)	18.0	19.9	26.9

5.3 Standard Effective Temperature

The standard effective temperature (SET) is both a comfort and heat stress index. The SET is defined as the temperature of still air of an imaginary indoor environment at 50% relative humidity and where the mean radiant temperature equals the air temperature, in which an imaginary occupant performing the same actual activity and wearing clothing standardized for the activity level, has the same skin heat loss, heat stress (skin temperature) and heat strain (skin wettedness) as in the actual environment (Parsons, 2014). The SET is calculated using the two-node bioheat model of Gagge et al. (1986). ASHRAE (2017) adopted SET for the calculation of thermal comfort under higher air speeds than the maximum allowable limit in the PMV model. Table 4 lists the SET thermal sensation scale (i.e. from cold to very hot) and its corresponding physiological state (Parsons, 2014). ASHRAE provides an online tool to calculate SET (https://comfort.cbe.berkeley.edu/).

Table 4. Thermal sensation scale of SET

SET (°C)	Thermal sensation	Physiological state
> 37.5	Very hot	Failure of thermoregulation
34-5 - 37.5	Hot	Profuse sweating
30.0 - 34.5	Warm	Sweating
25.6 - 30.0	Slightly warm	Slight sweating, vasodilation
22.2 - 25.6	Neutral	Neutral
17.5 - 22.2	Slightly cool	Vasoconstriction
14.5 - 17.5	Cool	Slow body cooling
10.0 - 14.5	Cold	Shivering

5.4 NRC improved indices for PMV and SET

The NRC has developed new improvements to the PMV and SET indices. The PMV improvement includes the extension of Fanger's PMV index to handle the comfort requirement for young and older people in wakeful and sleeping states with no limitation on clothing insulation, metabolic rate, temperature and humidity.

Figure 2 shows a comparison of Fanger's PMV index and the new improved index (MPMV) with measured thermal sensation votes in climatic chambers as reported in public literature (more details may be found in Laouadi (2021)). The comparison shows that the improved PMV index provides a better accuracy, particularly for the thermal comfort levels above the slightly warm (> 0.5) or below the slightly cool (< -0.5) ranges. For the neutral range (-0.5 to +0.5), all the indices are comparable.

For the SET model improvement for young adults, the models for sweating, skin blood flow and shivering of the original two-node model of Gagge et al. (1986) are improved and validated using publicly available experimental data (Ji et al., 2021a). Furthermore, the improved model includes a simplified model for sleep physiology (Laouadi et al., 2020a). For older people in a wakeful or sleep state, a new two-node model has been developed and validated using public experimental data. Figure 3 shows a comparison of the core and skin temperatures as predicted by the new models for young and older people and measured in the laboratory settings at a temperature of 36.5°C and relative humidity of 60% (Stapleton et al., 2014). The improved models produce better accuracy for the core and skin temperatures compared to the original model of Gagge et al. (1986). The Gagge et al. (1986) model for young adults was found to overestimate the skin blood flow and skin temperature by more than 1°C.

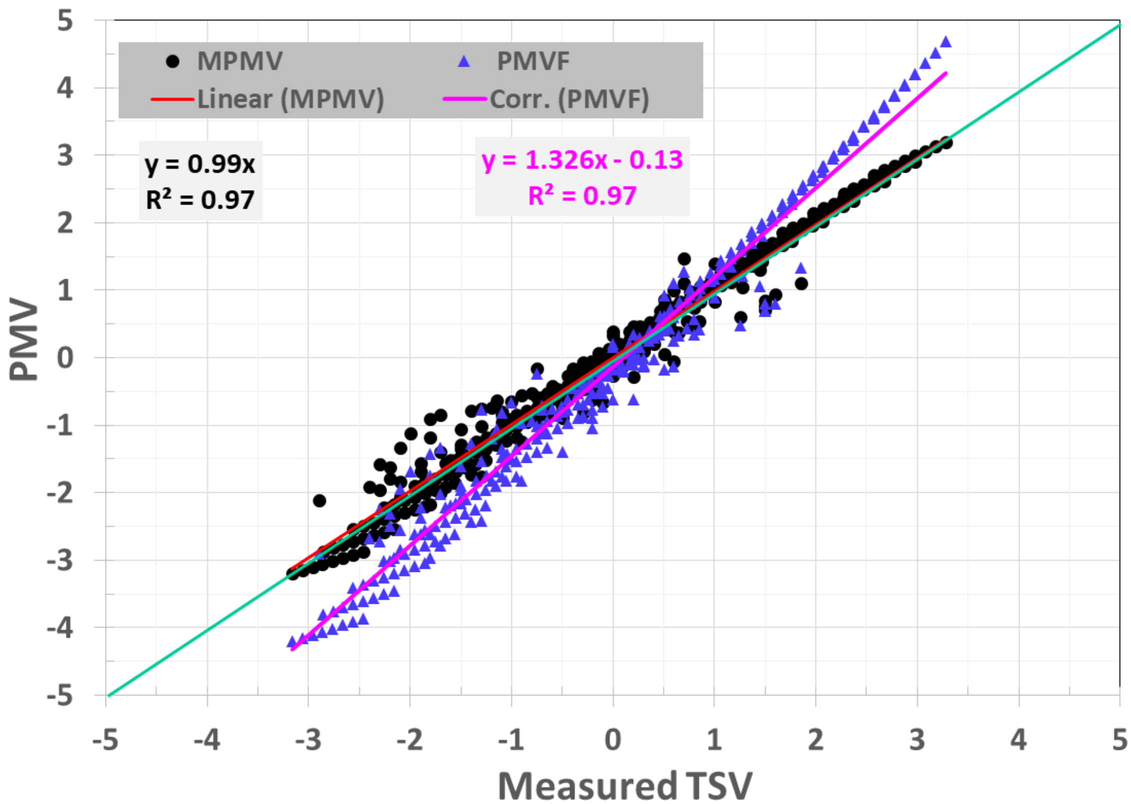


Figure 2. Comparison of Fanger's PMV index and the new improved index (MPMV) with measured thermal sensation votes (TSV) in climatic chambers (Laouadi, 2022)

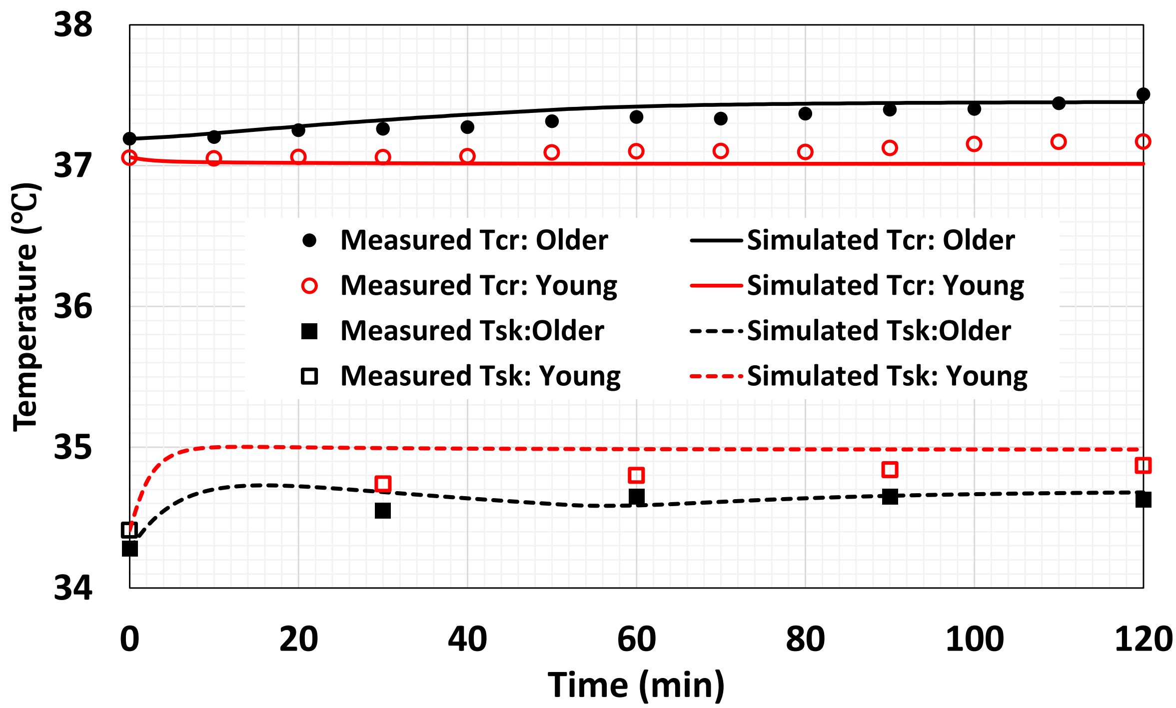


Figure 3. Comparison of the core and skin temperatures of young and older people with the measurement data of Stapleton et al. (2014)

5.5 Comfort requirement for young adults

The improved models for the PMV and SET indices are used to determine the comfort zone for young adults in a standing position under typical indoor exposure conditions. The thermal comfort zone is delineated by -0.5 ≤ PMV ≤ 0.5. Simulations were conducted to cover indoor conditions with operative temperatures = 18 to 40°C; relative humidity = 30 to 80%; air velocity = 0.1 to 0.5 m/s; metabolic rate = 1 to 1.4 met (typical indoor activity levels); and clothing insulation = 0.5 to 1 clo (typical summer clothing). The exposure time is fixed to 3 hours. Figure 4 shows the comfort zone in terms of SET and MPMV values. The comfort zone in terms of the corresponding values of SET lies between 23°C and 27°C with a neutral value of SET = 25°C (MPMV = 0).

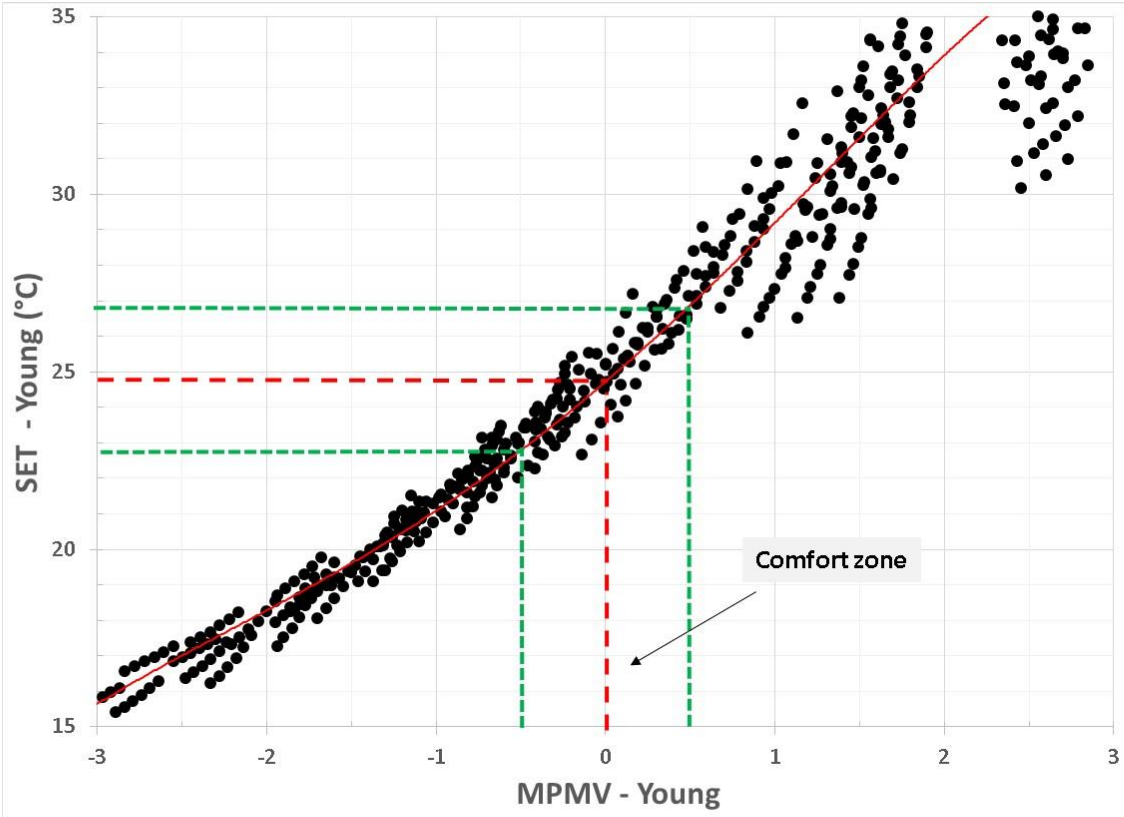


Figure 4. Thermal comfort zone for young adults in terms of MPMV and SET values

5.6 Comfort requirement for older people

Similar to young adults, simulations were conducted using the improved two-node models for young and older adults to cover typical indoor conditions as stated before. Two activity metabolic rates were used for older people: (1) older people having the same metabolic rate as young adults (but having different threshold temperature values for sweating, skin blood flow, and shivering); and (2) older people having a lower (30%) metabolic rate. Both metabolic rates are reported in the literature. For example, Stapleton et al. (2014) found young and older adults have approximately the same metabolic rate whereas Tsuzuki and Ohkufu (2002) found a 30% reduction in metabolic rate of a large group of people (109).

Figure 5 shows the comfort zone in terms of SET-Young (calculated for young adults) and its corresponding MPMV values for older people under the same indoor conditions. Older people having the same metabolic rates as young adults have roughly the same requirement for thermal comfort. The comfort values of SET-Young vary from 23.25°C to 27°C with a neutral value of 25.25°C at MPMV-Older = 0. This is consistent with Fanger's experimental findings where 118 older people with roughly 5% lower metabolic rates reported similar thermal sensation votes as young adults in climatic chambers (Fanger, 1970).

However, for older people having lower (by 30%) metabolic rates than young adults, their thermal comfort requirement is higher. The comfort values of SET-Young vary from 26°C to 29°C with a neutral value of 27.5°C at MPMV – Older = 0, which is 2.5°C higher than young adults. Older people would require warmer temperatures to get the same comfort level as young adults. This is as well consistent with the findings as reported in Van Hoof et al. (2017) and Schellen et al. (2010) in that older people prefer warmer (+2°C) environments than young adults to compensate for their lower metabolic rates and reduced peripheral skin blood flow.

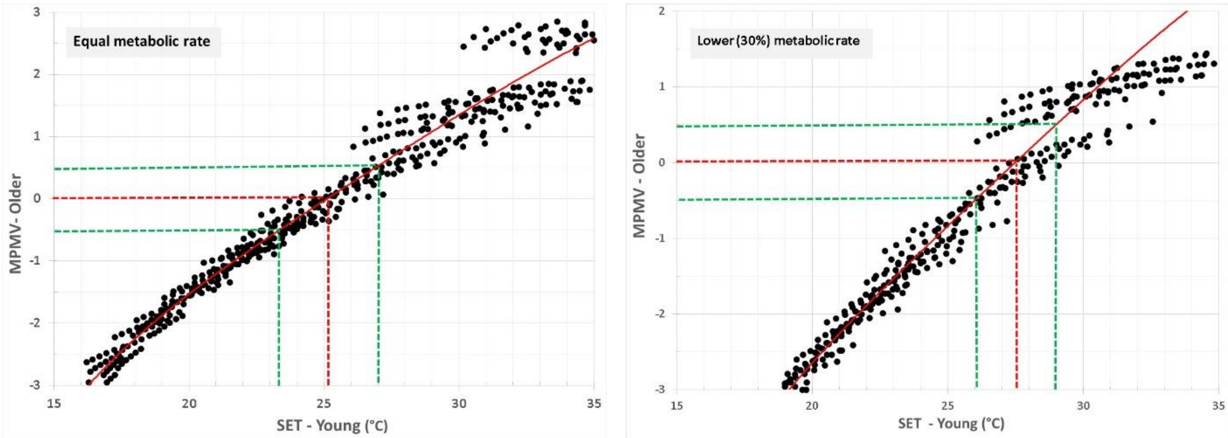


Figure 5. Thermal comfort zone for older people with equal and 30% lower metabolic rate than young adults

The comfort levels in terms of PMV are shown in Figure 6 for the two categories of older people. Older people having the same metabolic rates as young adults would report the same thermal sensation votes as young adults under the same environmental conditions. This is consistent with the findings of Fanger (1970), Soebarto et al. (2019) and Xiong et al. (2019), as shown in the figure. However, older people with lower metabolic rates than young adults would feel slightly cooler (TSV up to - 1) than young adults under the same conditions, or young adults would feel slightly warmer (TSV up to 0.75) than older people. This is consistent with the finding of Tsuzuki and Ohfulo (2002) and Schellen et al. (2010), shown in the figure. This finding may have some health implications under cold exposure conditions. If the thermal comfort requirements for young adults are imposed on older people, their core temperature would decrease and put them in potential health risk for hypothermia, especially for older people with limited mobility and adaptation opportunities to restore thermal comfort.

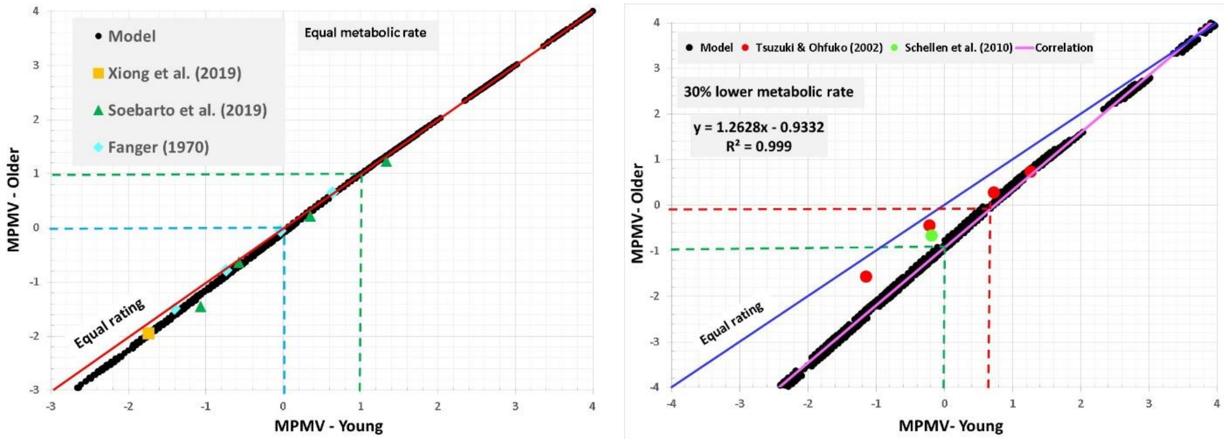


Figure 6. Relationship between the PMV indices for young and older people with equal and 30% lower metabolic rate

5.7 Comfort requirement for sleep

Studies have shown that the thermal comfort requirement for sleeping environments is different than for workplaces (Lan et al., 2017). Sleeping people have lower (30%) metabolic rate than wakeful people in a sedentary position. Furthermore, sleeping people cover their bodies while sleeping on a mattress, resulting in higher total clothing insulation values. Clothing insulation values can vary from season to season. In summer, typical clothing insulation values can take 1.38 clo (short sleeved pyjama + mattress) to 1.6 clo (long sleeved pyjamas + bed cover sheet + mattress) (Lin and Deng, 2008b). In winter, clothing insulation can take higher values such as 3.5 clo (long sleeved pyjamas + bed cover sheet + quilt + mattress), or higher. Due to their lower metabolic rate, sleeping people prefer mild to warm environments compared to wakeful people (Pan et al., 2012; Lan and Lian, 2016; Lan et al., 2017; Ngarambe et al., 2019). However, the comfort requirement for sleeping is not covered in any standard for built environments.

The improved models developed for the PMV and SET indices have been used to calculate the comfort requirement for sleeping people. The two-node bioheat model for SET incorporates a simplified model for sleeping as presented in Laouadi et al. (2020a). The improved MPMV index for sleeping is calculated by accounting for the neutral core and skin temperatures for sleep and the lower metabolic rate when sleeping. Simulations were conducted to cover typical indoor conditions with operative temperatures = 15 to 35°C; relative humidity = 30 to 80%; air velocity = 0.1 to 0.5 m/s; sleeping metabolic rate of young adults = 0.7 met; and clothing insulation = 1.38 to 3.5 clo. The exposure time was fixed to seven hours.

Figure 7 shows the comfort requirement for sleep in terms of the MPMV index and the corresponding SET values calculated for a young adult in a wakeful state but with a sleeping metabolic rate (0.7 met). Measured data on comfort for sleep from public studies carried out in climatic chambers and real buildings are included in the figure for comparison. The sleeping metabolic rate for older people was fixed at an average value of 0.56 met (20% lower than the young). The comfort zone for sleeping has a wide range, depending on the environmental conditions and clothing insulation (or season). For young adults, the corresponding values of SET-Young at MPMV = ± 0.5 vary between 26.75°C and 31.5°C with an average neutral value of SET-Young = 29°C. For older people, the corresponding values of SET-Young at MPMV = ±0.5 vary between 28.5°C and 33.5°C with an average neutral value of SET-Young = 31°C. Older people would thus require warmer temperatures for sleep than young adults. Model predictions are in good agreement with published measurement data as shown in the figure.

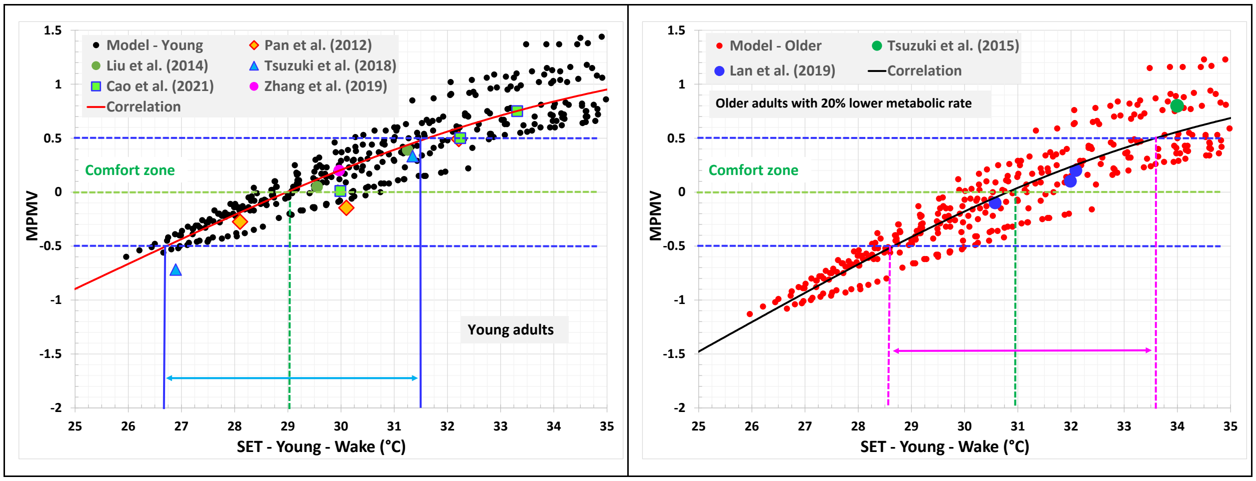


Figure 7. Sleeping comfort requirement for young and older people calculated as function of SET for wakeful young adults but with a sleeping metabolic rate (0.7 met). Sleeping older people are assumed having 20% lower metabolic rate (0.56 met).

5.8 Heat stress level of young and older people

The new bioheat models developed for the young and older people (Li et al., 2021a,b) have been used to predict the heat stress levels of young and older people under typical indoor conditions as stated before. The heat stress levels are indicated by the core (T_{cr}) and skin (T_{sk}) temperatures, skin heat exchange by sweat evaporation (evaporative heat) and convection and radiation (dry heat) with the adjacent environment, skin wettedness (ratio of skin evaporative heat loss to maximum evaporative heat loss), and body water loss by sweating and respiration. Simulations were conducted for an exposure time of 3 hours.

Figure 8 compares the results obtained for young adults and older people having the same metabolic rate as the young. Measured body temperature data from public studies are also included in the figure for a comparison purpose. The findings are:

- Older people have higher core temperatures (by up to 0. 5°C) and slightly lower or equal skin temperatures under warm or hot exposure conditions (> 30°C) than young adults. Under cool or cold exposure conditions (< 25°C), the skin temperature of older people is, however, higher (by

up to 0.75°C) for sedentary activities due to a weakened vasoconstriction (resulting in a higher skin blood flow), or lower (by up to 1.5°C) under non-sedentary activities (metabolic rate > 1 met) due to a weakened vasodilation (resulting in lower skin blood flow) than young adults.
- Skin dry heat loss or gain (negative values) of older people under warm or hot exposure is approximately equal to young adults (since the skin temperatures are approximately equal). However, the evaporative heat loss of older people is slightly higher than young adults under warm/hot exposure due to higher core temperatures that triggers sweating, but significantly higher under cool or cold exposure conditions (< 25°C), particularly at high activity levels (> 1 met).
- Skin wettedness of older people is higher than young adults, particularly at cool/cold exposure conditions and high activity levels.
- Body water loss (for 3 hour exposure duration) by sweating and respiration is approximately equal under warm exposure conditions (around 30°C), but becomes significantly lower under hot exposure conditions (> 35°C) due to impaired sweating of older people.

Figure 9 compares the results obtained for young adults and older people having 30% lower metabolic rate than young adults. Measured body temperature data from public studies are also included in the figure for a comparison purpose. The findings are:

- Under warm or hot exposure conditions (> 30°C), the core temperature of older people is higher (by up to 0.3°C) at the onset of skin blood vasodilation and sweating (T_{cr} around 37°C), but becomes lower (by up to 0.3°C) when sweating is fully developed. Under cool or cold exposure conditions, the core temperature of older people becomes lower (by up to 0.4°C) than young adults. The skin temperature of older people is consistently lower (by up to 2°C) than young adults under warm or hot exposure conditions, but higher (by up to 0.5°C) under cool or cold exposure conditions.
- Skin dry heat loss (or gain at higher ambient temperatures) of older people under warm or hot exposure conditions is lower (or higher) than young adults depending on the indoor conditions. The skin evaporative heat loss of older people is significantly lower than young adults due to impaired sweating and lower core and skin temperatures, which trigger sweating.
- Skin wettedness of older people is significantly lower than young adults.
- Body water loss (for 3 hour exposure duration) by sweating and respiration under warm or hot exposure conditions is significantly lower.

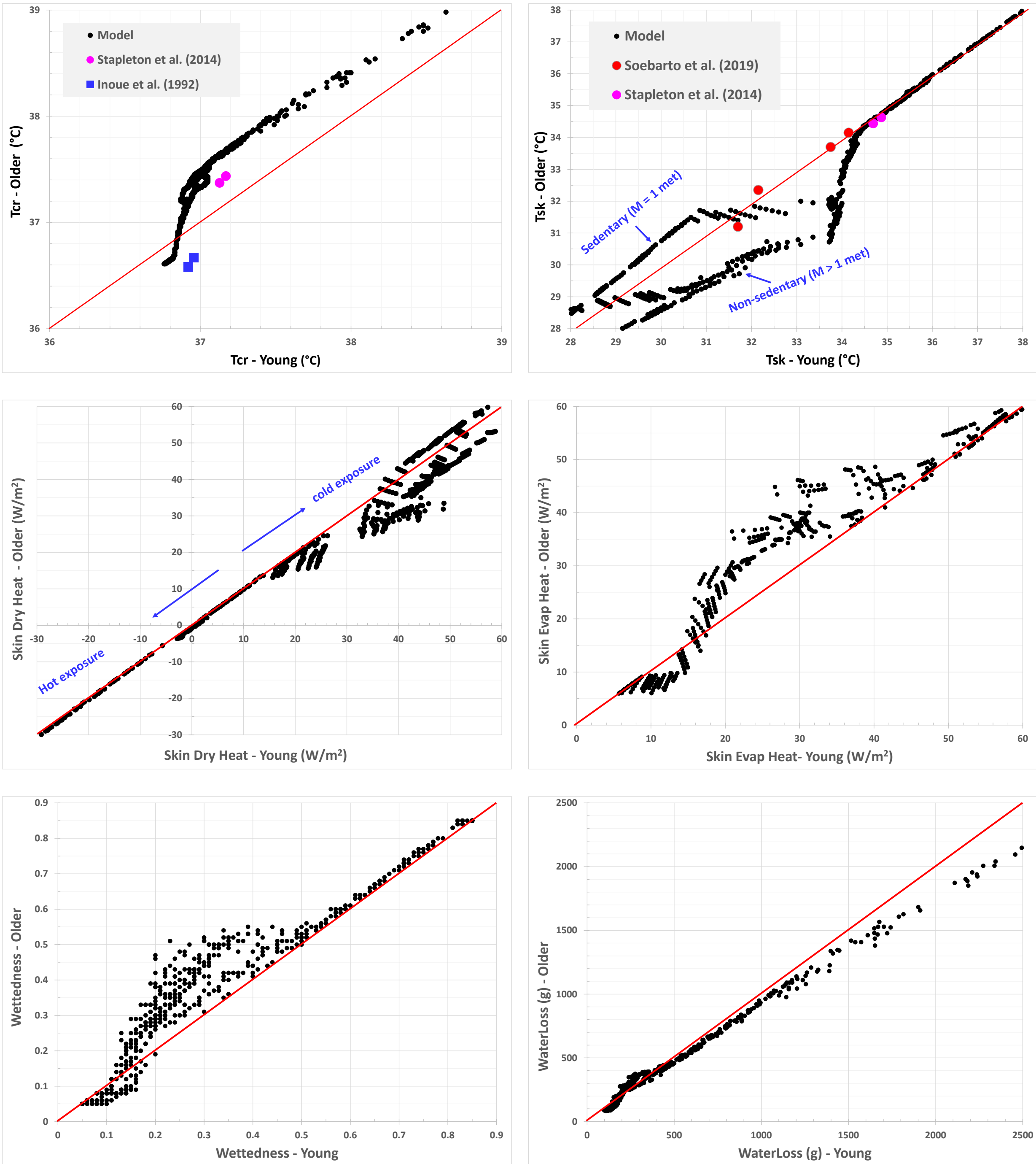


Figure 8. Comparison of core and skin temperatures, skin dry and evaporative heat exchanges, skin wettedness and body water loss (for 3 hrs) of older people with young people under typical indoor conditions. Older people are assumed having the same metabolic rate as the young.

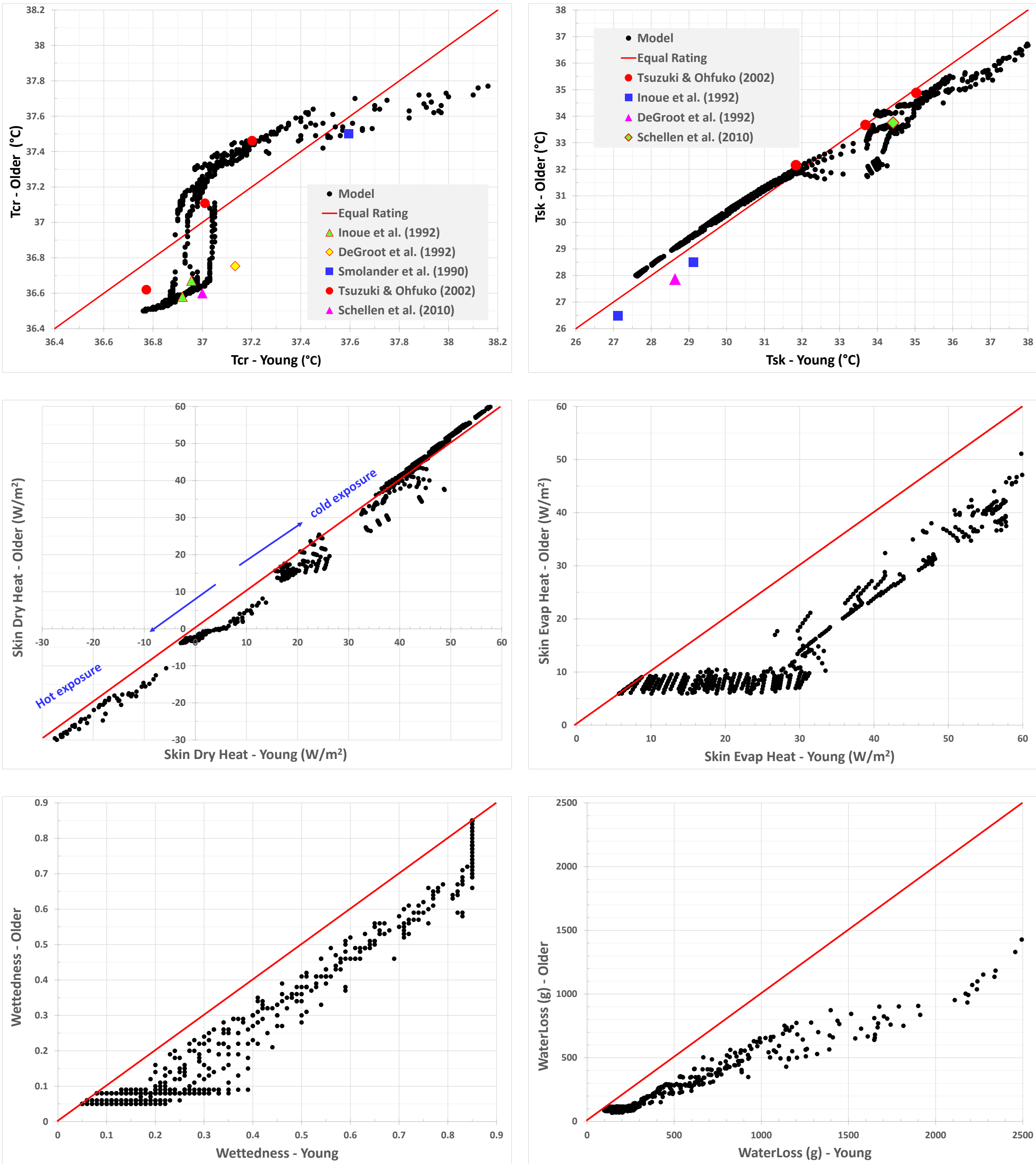


Figure 9. Comparison of core and skin temperatures, skin dry and evaporative heat exchanges, skin wettedness and body water loss (for 3 hrs) of older people with young people under typical indoor conditions. Older people are assumed having 30% lower metabolic rate as the young.

6 OVERHEATING IN BUILDINGS

6.1 Introduction

Overheating in buildings arising from extreme heat events (EHEs) of local climates is a growing health concern in many countries (HC, 2011; CIBSE, 2013; Saman et al., 2013; Quinn et al., 2014; Eames, 2016). In general terms, overheating relates to the thermal comfort and health of building occupants exposed to daily warm or hot indoor conditions. Overheating may be found in free-running or naturally ventilated buildings, buildings with limited capacity or intermittent use of air conditioning, and buildings that experience extended periods of power outages or HVAC failure. In those buildings, the indoor conditions are a result of the outdoor conditions. However, the indoor conditions may be altered by building constructions (e.g. insulation levels of envelopes, air leakage rate, windows, and other relevant factors), and operation of HVAC systems (i.e. air-conditioning, and ventilation systems). Furthermore, occupant behavior (e.g. use of appropriate clothing; use of ventilation fans, opening windows, etc.) and adaption to warm climates may exercise a significant influence on the overheating sensation. Persisting warm or hot indoor conditions over several days may strains the human physiological system and therefore lead to serious health injuries or even death, particularly for occupants vulnerable to heat. To reduce such effect on occupant health, buildings should be designed, or retrofitted and operated to mitigate the risk of overheating under such extreme climatic conditions. The following sections present a methodology to evaluate overheating risk in buildings.

6.2 Definition of overheating

There is no universal or agreed-upon definition of overheating in buildings (Anderson et al., 2013; ZCH, 2016). In the context of this guideline document, overheating is defined as:

The cumulative effect on the thermal comfort (or heat stress) and health of building occupants directly exposed to continuous daily indoor heat events.

A daily indoor heat event is itself defined as:

A heat event with warm temperatures that occurs daily over at least a prescribed number of hours during daytime and triggers a physiological response and action of occupants to restore thermal comfort.

A physiological response is triggered when the indoor conditions are above the neutral comfort conditions and restoring thermal comfort is possible when the indoor conditions reach some threshold values in the discomfort range. The selection of such threshold values is discussed in the next section.

In some built environments, comfort is required not only for active occupants during daytime, but also for sleep during nighttime. Sleep is regulated by a different physiological mechanism but exposure to warm or hot conditions during nighttime can disturb or deprive sleep. Sleep disturbance will in turn exacerbate the physiological response of occupants to heat events during the following day (CIBSE, 2015; NASEM, 2016; Kenny et al., 2018). If this cumulative effect continues from day to day, it will potentially lead to health issues to occupants. This cumulative effect therefore requires that building occupants are connected with the spaces they occupy during the continuous heat events.

Overheating as defined in this guideline document is centered on occupants and their connected spaces during heat events. The occupied spaces may therefore be dynamic in a day course. This reflects situations where occupants can adapt to heat by moving from a warm to a cooler space, or perform activities in one space during daytime and move to another different space for sleep during nighttime. This treatment of overheating is different from evaluating overheating for fixed spaces and not connected with occupants during exposure to heat events. For example, in residential buildings, evaluating overheating for living rooms will not account for the cumulative effect of heat on occupants who dwell in living rooms during daytime and sleep in bedrooms during nighttime. Similarly, evaluating overheating for bedrooms will cover only sleep disturbance and ignore the effect of heat on occupants during daytime exposure.

Evaluation of overheating will require a metric for thermal comfort or heat stress. In this guideline document, the transient standard effective temperature index (named t-SET, calculated at each time step as opposed to SET, which is calculated at the end of exposure time) is used and computed using the developed physiological models for young and older people (Ji et al., 2021a,b)) as presented in the previous sections. During exposure to continuous indoor heat events of duration N (days) where occupants can occupy many spaces in which they perform activities during daytime and one space during nighttime for sleep, the magnitude of overheating (noted as SETH) is expressed by the following relationship (Laouadi et al., 2020b):

$$\mathrm{SETH} = \sum_{i=1}^{N} (\mathrm{SETH_n} + \mathrm{SETH_d})_i \tag{1}$$

With:

$$\mathrm{SETH_n} = \sum_{sleep}^{wakeup} (\text{t-SET}_\tau - \mathrm{SET_n})^+ \cdot \Delta\tau \tag{2}$$

$$\mathrm{SETH_d} = \sum_{wakeup}^{sleep} (\text{t-SET}_\tau - \mathrm{SET_d})^+ \cdot \Delta\tau \tag{3}$$

Where:

t-SET_τ : hourly value of t-SET of the space being occupied at hour (τ) during day or night time (°C);

$\mathrm{SET_n}$: threshold value of SET for a sleeping occupant during nighttime (°C);

$\mathrm{SET_d}$: threshold value of SET for an active (wakeful) occupant during daytime (°C);

$\mathrm{SETH_d}$: magnitude of a heat event occurring over a daytime period (°C·h);

$\mathrm{SETH_n}$: magnitude of a heat event occurring over the preceding nighttime period (°C·h);

SETH : magnitude of overheating (°C·h);

$\Delta\tau$: calculation time step (h).

The symbol ($^+$) in equations (2) and (3) indicates that only positive values are considered.

Equation (1) distinguishes various types of indoor heat events with different magnitudes and durations over a summer period. A daily indoor heat event is counted only if its daytime magnitude ($\mathrm{SETH_d}$) exceeds an arbitrarily minimum value ($\mathrm{SETH_{d,min}}$). The latter should be a function of the selected threshold value of SET_d. A high value of $SETH_{d,min}$ may be chosen for low values of SET_d, or vice versa. In this guideline document, $SETH_{d,min}$ is set to 4°C·h to limit the percentage of body water loss by sweating and respiration to lower than 1% (the maximum allowable limit is 3% according to the ISO (2018)) when occupants are exposed to indoor conditions of one degree t-SET above the threshold value SET_d for four hours. The preceding nighttime magnitude ($SETH_n$) is counted in equation (1) only if the daytime magnitude ($SETH_d$) exceeds $SETH_{d,min}$. In other words, sleep disturbance during the preceding nighttime only affects active occupants under daytime heat stress. Multiple continuous indoor heat events are separated by a recovery period of at least one day with $SETH_d \leq SETH_{d,min}$.

Evaluation of equations (1) to (3) needs reference occupants undergoing the exposure to indoor heat events. Furthermore, day and night time exposures should be clearly defined in terms of time schedules. The reference occupant may vary with the built environment they occupy during the heat events. For residential buildings, the reference occupant is assumed to be in a sedentary seated position (metabolic rate of 1 met) and wearing typical summer clothing (0.5 clo) during day time exposure. During nighttime exposure, the reference occupant is assumed in a sleeping (metabolic rate 0.7 met for healthy young adults) state, wearing short-sleeved top and bottom pyjamas and, laying on a mattress bed (total clothing insulation of 1.38 clo according to Lin and Deng, 2008b). The schedules for day and night time exposures depend on building type as well. For residential buildings, nighttime exposure is assumed between the sleep start hour of 10:00 pm and wakeup hour of 7:00 am. Daytime then starts from the wakeup hour and ends at the sleep start hour. For office and school buildings, the schedule of daytime takes on the schedule of working hours as set in applicable building codes. It should be noted that in the context of overheating, a complete day of exposure starts from the sleep start hour of the previous night and ends at the sleep start hour of the current day.

Building spaces occupied during the day and/or night time vary with building type. For residential buildings, such as dwellings and suites in multi-unit residential buildings, occupants are assumed to dwell in either the living rooms (or dedicated cooling rooms if present) during daytime or bedrooms during nighttime. Those spaces (living rooms, dedicated cooling rooms, bedrooms) should be indicated as separate thermal zones in any field or simulation study to apply equations (1) to (3) for overheating risk analysis. The indoor conditions of the living (or dedicated cooling) room spaces are assigned to daytime exposure, and those of bedrooms are assigned to nighttime exposure to calculate the hourly values of t-SET. For office or school buildings, spaces are only occupied during daytime and therefore equation (2) does not hold. For other buildings where occupants occupy a single space for the entire day (such as patient rooms in hospital buildings), both equations (2) and (3) apply.

6.3 Characterising overheating events

As stated before, an ***overheating event consists of a number of continuous daily indoor heat events***. Multiple overheating events are therefore expected to occur during a summer season. Such multiple overheating events are distinguished from each other by their attributes. One can define three attributes as below:

Duration is measured in terms of the number of days of continuous daily indoor heat events.

Severity is measured in (°C·h) and indicates the magnitude of the overheating event as given by equation (1). Severity takes into account the heat stress level (deviation of t-SET from the threshold value) and the exposure time of the overheating event.

Intensity is measured in (°C) and calculated as the ratio of severity to duration (expressed in hours). Intensity indicates the average deviation of t-SET from the threshold values over the entire duration of an overheating event.

As per those attributes, many types of overheating events may occur during the summer period. One can distinguish three major types, namely: long, intense and severe. Long overheating events are usually mild, and intense overheating events usually occur over shorter periods of time. Severe overheating events range between long and intense overheating events. Other types of overheating events such as long and intense, long and severe, or intense and severe may occur as well. These types of overheating events may have different effects on the comfort and health of building occupants. For example, long or severe overheating events may result in body dehydration (body water loss by sweating) whereas intense overheating events may result in hyperthermia (quick increase of body core temperature above 38°C) which may lead to serious health issues such as heat stroke or even death. Those types of overheating events are therefore very important to distinguish in the summer when undertaking an overheating risk analysis.

6.4 Selection of threshold values

The threshold values of t-SET for occupants in the sleeping and active (wakeful) states (SET_n, SET_d) during night and day time exposure, respectively, are chosen depending on building type and the vulnerability of occupants to thus ensure their health is not affected by exposure to indoor heat events. Mortality studies showed that the onset of daily excess counts of mortality occurred when the outdoor maximum temperatures were at the limit between thermal comfort and discomfort (25 to 28°C), particularly in temperate summers (Casati et al., 2013). Given this fact, a fundamental criterion to select the threshold values for t-SET is that they should not be in the range of thermal discomfort that would induce irreversible health effects. For example, the discomfort range that induces excessive sweating may result in health issues (e.g., heat syncope, heat exhaustion, dehydration, etc.) that cannot be eliminated by simple adaptation measures such as changing clothing, reduced activity level, portable fan ventilation, opening windows, and other similar actions to reduce sweating. In this regard, the discomfort range that should be selected is the one that is tolerable by most healthy occupants and for which occupants can restore thermal comfort by simple adaptation measures available to them. This discomfort range corresponds to the slightly warm (or slight sweating) range (skin wettedness < 30%) when occupants are active during daytime. The corresponding value of SET_d is 30°C (Parsons, 2014) for healthy and un-acclimatized young occupants who are free to adapt to heat (such as changing their clothing, moving from a warmer space to a cooler space, open windows for space ventilation, use ceiling or portable cooling fans, taking cool showers, ingesting cold commodities such as cool drinks or crashed ice, etc.) to restore thermal comfort, or 31.2°C for naturally heat acclimatized occupants (Laouadi et al., 2020b). The value of SET_d (30°C) for un-acclimatized occupants is close to the measured average value of SET = 29.3°C (25.9 to 32.8°C) at which occupants started to feel too warm and intended to change the conditions to restore comfort (Meinke et al., 2017). Zhang et al.

(2016) found out that the SET value for acclimatized occupants living in rural warm areas that corresponds to a slightly warm sensation (PMV = 1) is 31.18°C, which is very close to the aforementioned value of 31.2°C. For healthy young adults but with limited opportunities for heat adaptation, the threshold value of SET_d for an active occupant is set so that sweating is minimised. This corresponds to the upper limit of the comfort range with SET_d = 27°C for un-acclimatized occupants (Figure 4) and 28.2°C for acclimatized occupants. It should be noted that the SET_d value for acclimatized occupants is within the reported comfort range of SET = 26.7 ± 1.4°C for urban acclimatized occupants living in naturally ventilated buildings (Zhang et al., 2016).

Older people are less sensitive to heat as having higher core temperature than young adults under warm exposure conditions (Figures 8 and 9). Therefore, to protect the health of such vulnerable people, the threshold values of SET_d should be chosen to avoid any significant increase in their core temperature and heart rate required for the increased skin blood flow. For healthy older people who can adapt to heat, the results of Section 5 are used. The threshold value SET_d is set to the upper limit of the comfort range (PMV = 0.5). For older people having an average reduction in their metabolic rate (20% lower than young adults), the corresponding SET_d is determined to be SET_d = 28.2°C (29.4°C for acclimatized occupants). For older people with limited opportunities for heat adaptation, the threshold value of SET_d is set so that sweating is minimised (PMV = 0). The corresponding threshold value of SET_d is 26.8°C (28°C for acclimatized occupants).

For sleep comfort, the threshold values of SET_n are set as the average value corresponding to PMV = 0 and 0.5. From Figure 7, the corresponding threshold values of SET_n for young and older people are 30°C and 32°C, respectively.

Table 5 lists suggested thresholds values of SET for various types of free-running or partially air-conditioned buildings with young and older occupants with or without heat adaptation opportunities. For secondary schools, occupants (adolescents) are treated as young adults, but with a higher (by10%) metabolic rate. For primary schools, students (under 12 year old) are assumed having higher (by 10%; Smith, 2019) metabolic rate than young adults, but with lower thresholds values of SET to limit thermal comfort to PMV = 0.5 since they have limited capacity to sweat and higher core temperature than young adults (Smith, 2019). For senior homes, occupants are assumed requiring some level of support (independent living style). To protect their heat-related health, the corresponding threshold values of SET are set to limit thermal comfort to PMV = 0.5. For long term care homes (LTCH), occupants are considered older people requiring full support (assisted or nursing living style). To protect their heat-related health, the corresponding threshold values of SET are set to limit thermal comfort to PMV = 0. For patient rooms (in hospitals), occupants are assumed laying on a bed all day, and the corresponding threshold values of SET are set to limit thermal comfort to PMV = 0. The metabolic rate of older people is fixed to an average value of 20% lower than young adults.

Table 5. Suggested threshold values of SET_d and SET_n for un-acclimatized (acclimatized) occupants by type of buildings under free-running or partially air-conditioned modes+

Building Type ↓	SET_d (°C)					SET_n (°C)
	Reference young occupant	Young adults		Older adults		Young / Older adults
		with adaptation	without adaptation	with adaptation	without adaptation	
Residential	1 met & 0.5 clo (wake); 0.8 met & 1.38 clo (sleep)	30 (31.2)	27 (28.2)	28.2 (29.4)	26.8 (29)	30/32
Office	1.1 met & 0.57 clo (wake)	30 (31.2)	27 (28.2)	28.2 (29.4)	26.8 (29)	N/A
High school	1.2 met & 0.57 clo (wake)	30 (31.2)	27 (28.2)	N/A	N/A	N/A
Primary school	1.2 met & 0.57 clo (wake)	27 (28.2)	25 (26.2)	N/A	N/A	N/A
Senior home	1 met & 0.5 clo (wake) 0.8 met & 1.64 clo (sleep)	N/A	N/A	28.2 (29.4)	N/A	32
LTCH	1 met & 0.5 clo (wake) 0.8 met & 1.64 clo (sleep)	N/A	N/A	N/A	26.8 (28)	32
Hospital (Patient room)	1 met & 1.57 clo (wake) 0.8 met & 1.64 clo (sleep)	N/A	27 (28.2)	N/A	26.8 (28)	30/32

+N/A indicates values are not applicable. Older people are assumed having 20% lower metabolic rate than young adults.

6.5 Criteria of overheating

Overheating events have to be subject to some limiting criteria to permit declaring hazardous overheating conditions for occupied building spaces. The selection of such criteria is therefore important to ensure the health of building occupants is protected during extreme overheating events. The proposed method is based on linking the magnitude (severity) and intensity of overheating events to heat-related health outcomes. The most important health outcomes are body dehydration arising from excessive sweating, and increase of body core temperature beyond a threshold value.

Dehydration was the leading cause of mortality followed by heatstroke (core temperature > 40°C) during the heat wave that occurred in France in 2003 (Fouillet et al., 2006). Dehydration is also one of the most frequent causes of hospitalization of older people (Garriguet, 2008; Feliciano et al., 2010). The International Standard Organisation (ISO, 2018) recommends the maximum allowable dehydration rate of 3% of body weight for healthy young adults in industrial workplaces, and indicates that higher dehydration rates are associated with increased heart rates and reduced sensitivity to sweating due to reduced blood plasma volume. However, for vulnerable people, the maximum dehydration rate should be lower due to their physiological age-related changes (e.g., kidney function, thirst perception, lower body water content; Volkert et al., 2004). For example, older people are less sensitive to thirst and heat, and those people who are ill have limited mobility to acquire a sufficient volume of water to permit rehydration if they do not receive continuous nursing support. The situation can be exacerbated by cardiovascular and renal diseases and medications (Van Loenhout et al, 2016). Dehydration rates as low as 2% of body weight for older people can have significant health issues such as lower endurance and increased risk of heat exhaustion and fatigue, and impaired cognitive functions and performance responses (Begum and Johnson, 2010; Aphamis et al., 2019). If people can freely rehydrate themselves (by drinking beverages to replace water loss by sweating), the threshold is relaxed to a higher value. Studies in coalmine industries found that 50% of workers had an average rehydration rate (water replacement) of 60% for exposure up to six hours in hot conditions (i.e. 28 to 32°C), and 95% of workers had rehydration rates greater than 40% (ISO, 2018). From community surveys undertaken in Canada (Jones et al., 2019), it was found that average age adults (31-50 years) and older people (> 51 years) respectively drank, on average, 2031 and 1791 ml/day of beverages. This corresponds to hydration rates of 79% for average age adults and 70% for older people based on the Canadian recommended average fluid intake of 2550 ml/day for sedentary subjects (3 litres for men and 2.2 litres for women of all ages). Similar studies in Europe found that a hydration rate of 81% is common in the adult population (Aphamis et al., 2019). A substantial number of elderly aged above 85 years old were found to drink one litre/day (hydration rate of 63% based on a recommended 1.6 litre/day for older people; Rikkert et al., 2009). Studies in long term care homes for older people receiving continuous nursing support showed that 20 to 31% of older residents were dehydrated (Begum and Johnson, 2010; Jimoh et al., 2019). Studies on hydration rates of people in community and institutional buildings during extreme heat events are, however, not available. Under long exposure to such extreme heat events, body water loss by sweating can be significant (up to 1 litre/h is common), resulting in higher dehydration rates of people. Rehydration rates of people in community and institutional buildings during extreme heat events are therefore based on conservative assumptions. The proposed method assumes an average rehydration rate of 80% for young adults, with a threshold body dehydration rate of 3% as set in ISO (2018). With the 80% rehydration rate the allowable dehydration rate can then be relaxed to 3% / (1 - 0.8) = 15%. For healthy older people, the same rehydration rate of 80% is assumed but with a threshold body dehydration rate of 2%. This brings the allowable dehydration rate to 10%.

As for limiting the body core temperature, heat exposure standards for workplaces set a maximum value for the core temperature to 38°C for healthy average age adults under sustained heat exposure of up to 8 hours (NIOSH, 1986; CCOHS, 2018; ISO, 2017). This threshold corresponds to a hot thermal sensation with profuse sweating (SET > 37.5°C). This, however, may not be suitable for sustained exposure during long overheating events that may last many days. Furthermore, for vulnerable people this maximum value can be very dangerous to their health. Therefore, a lower threshold limit for core temperature should be used. The proposed value of the limit core temperature is set to 37.6°C (slightly above the normal range of 36 – 37.5°C; Kuht and Farmery, 2018) for young adults, which corresponds a hot sensation level (SET > 35°C). For healthy older people, a core temperature of 37.6°C corresponds to a core temperature for young adults of 37.2°C (Figure 8). The difference in the core temperature between older people and young adults is 0.4°C, which is within the reported measured difference of 0.20 to 0.35 ± 0.20°C (Sagawa et al., 1988; Stapleton et al., 2014).

To determine the relationships between the attributes of overheating events and the heat related health outcomes of occupants, overheating calculations were conducted for occupants in archetypical single detached homes, representative of old (1980s) and current (NRC, 2015) construction practices, for three Canadian cities (Montreal (PQ), Ottawa (ON), Toronto (ON)) during overheating events, and where the home assumed typical residential indoor settings over the summer season. Both the intensity and severity of overheating events were determined, as was the maximum core temperature of occupants and their cumulative body water loss as a function of body weight due to sweating and respiration (calculated using the developed two-node bioheat model; Ji et al., 2021a,b). Details of this study is presented in Laouadi et al (2020b).

Figure 10 and Figure 11 show the severity and intensity values of overheating events versus the cumulative (over duration of overheating event) percentage of body water loss for young adults, respectively. The severity index of overheating events correlates well with the cumulative body water loss percentage. However, the intensity index correlates to a greater extent with the maximum body core temperature. Based on the limiting criterion for body water loss, as previously specified, overheating is declared when the severity index (SETH) is greater than 230 ±42 (°C*h). However, the core temperature does not reach the threshold limit of 37.6°C under typical indoor residential settings for the selected Canadian cities of this study. The situation may be different in other locations with warm or hot climates with dry or humid conditions.

Figure 12 and Figure 13 show the severity and intensity values of overheating events versus the cumulative percentage in body water loss for healthy older people, respectively. Similar to that given in (Figure 10 and Figure 11), the severity index of overheating events correlates well with the cumulative body water loss percentage and the intensity index correlates, again, to a greater extent with the maximum body core temperature. Based on the limiting criterion for body water loss percentage for older people as given previously, overheating is declared when the severity index (SETH) is greater than 117 ±30 (°C*h). Based on the threshold core temperature for older people, overheating is declared if the intensity of overheating events exceeds 4 ±0.2°C under typical indoor residential settings for the selected Canadian cities.

It should be noted that the overheating criteria, as presented, were developed for an assumed rehydration rate of 80%. Further research is needed to determine common values of rehydration rates of occupants in typical building settings subject to extreme overheating events. The relationships in Figure 10 and Figure 12 are to be used to determine the severity limit criterion of overheating events for different rehydration rates in Canadian locations.

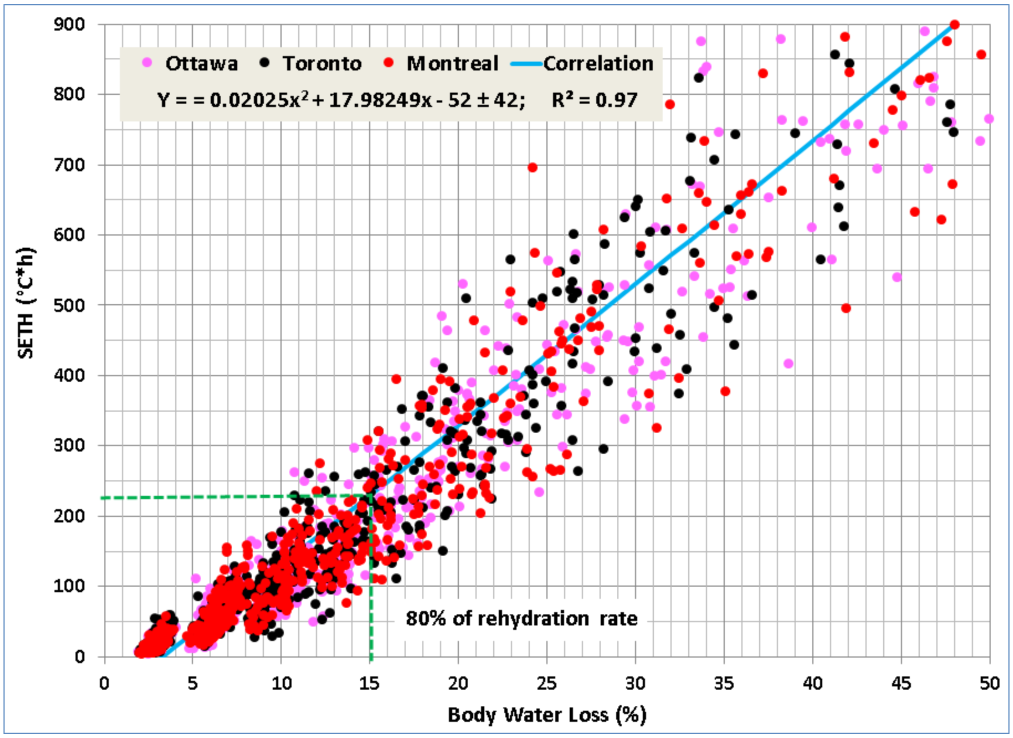


Figure 10. Severity of overheating events (°C*h) versus cumulative body water loss (%) for young adults

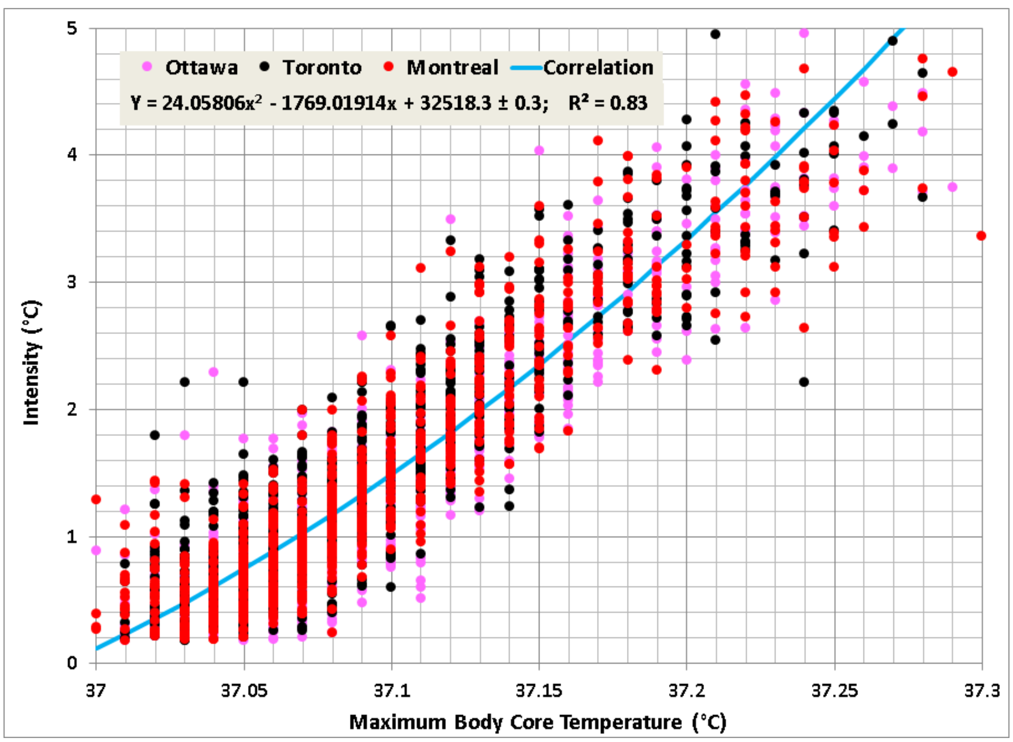


Figure 11. Intensity of overheating events (°C) versus maximum body core temperature (°C) for young adults

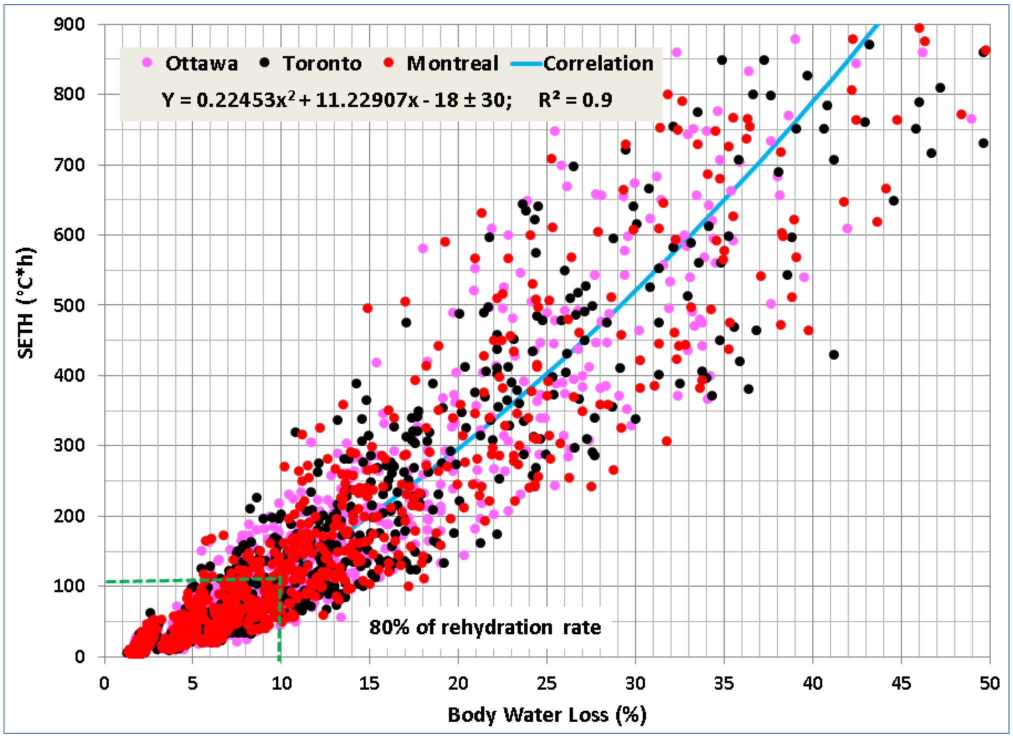


Figure 12. Severity of overheating events (°C*h) versus body water loss (%) for healthy older people

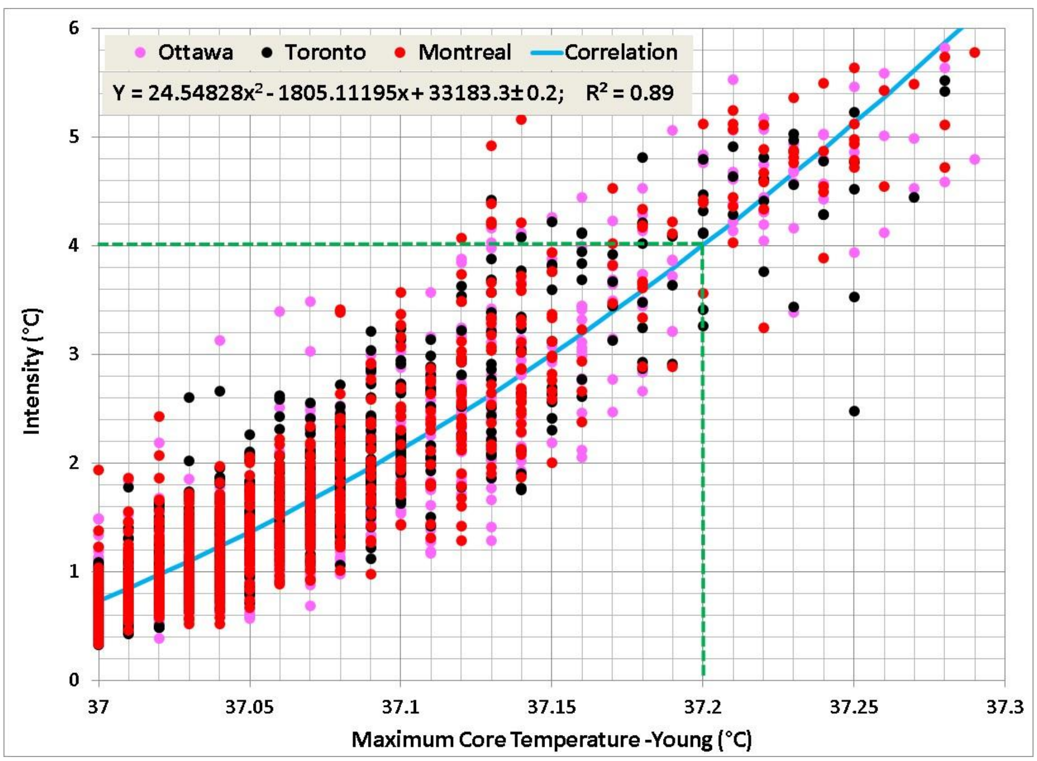


Figure 13. Intensity of overheating events (°C) versus maximum body core temperature – Young adults (°C) for healthy older people

7 OVERHEATING RISK FACTORS

The factors that increase the overheating risk in built environments are basically the ones that directly or indirectly affect the indoor conditions and weaken the physiological response of occupants to heat. The key factors are summarized below.

7.1 The outdoor environment

The conditions of the local outdoor environment exercise a direct influence on indoor conditions. An example of this is the outdoor extreme heat events (or heat waves) as well as other outdoor confounding factors that affect the health of building occupants. The outdoor factors that have a significant effect on overheating are:

- **Temperature**. Outdoor heat is transported to the indoor space through building envelopes, air infiltration and ventilation through intentional openings (i.e. windows). The higher the outdoor temperature, the greater the overheating risk.
- **Relative humidity**. Outdoor humidity is transported to the indoor space mainly by air infiltration and ventilation, particularly in old leaky buildings and naturally ventilated buildings. High humidity levels reduce the effectiveness of evaporative cooling from the skin surface of the body through the release of sweat.
- **Wind speed**. Wind speed increases air infiltration and ventilation. It may increase or reduce the risk of overheating based on the level of the outdoor humidity. In naturally ventilated buildings, wind speed reduces the overheating risk by increasing the air velocity indoors and thus providing a cooling effect to the body's skin surface.
- **Solar radiation**. High solar radiation (during sunny days) provides a significant amount of heat indoors through unshaded windows, thus increasing the indoor temperatures and the mean radiant temperature if occupants are in direct exposure to sunlight.
- **Air pollution**. Air pollution is a confounding factor that affects the health of building occupants, particularly if the outdoor air is not adequately filtered by building HVAC systems.
- **Local climate**. Local cold or temperate climate affects the acclimatization to heat of the population, particularly in late spring and the beginning of summer. People living in warm or hot climates are naturally heat acclimatized.

7.2 The building

Buildings alter the indoor thermal conditions. In the western world, people spend up to 90% of their time indoors (IOM, 2011) and are therefore exposed most of the time to the indoor thermal conditions rather than that of the outdoors. Factors related to the built environment that may increase overheating risk of building occupants include:

- **Insulation levels and air leakage of building envelopes**. High insulation and tight envelopes reduce heat gains from the outdoor environment but also limit the release of trapped indoor heat gains to the outdoors. If the indoor space is not well ventilated, the trapped heat will increase the risk of overheating.

- **Window solar shading**. Unshaded windows result in high solar heat gains, which will increase the indoor temperatures and therefore the overheating risk.
- Internal heat gains. High internal heat gains from equipment, lighting, occupants, cooking, service hot water, etc. increase indoor temperatures.
- **Free-running or naturally ventilated buildings**. The indoor conditions in those buildings are not controlled and therefore are subject to high indoor temperatures than in air-conditioned buildings. In Canada, about 39 to 50% of residential buildings do not have air conditioning (Tables 6 and 7 below). For commercial and institutional buildings, about 31.2 % of the total buildings (or 17% of total floor area) do not have air conditioning (NRCan, 2012). Non air-conditioned schools (primary and secondary), office buildings (non-medical), and hospitals make up about 36.3%, 11.4%, and 1.3% of the total commercial and institutional buildings, respectively.
- **Non adequately-ventilated buildings**. Adequate ventilation is necessary to remove indoor contaminants. High indoor temperatures increase chemical reactions and material off-gazing, thus resulting in more production of indoor contaminants that may affect the health of building occupants.
- **Occupant density**. Buildings with high occupant density (e.g., social housing) may result in poor indoor air quality and respiratory health issues, which in turn may weaken the physiological response to heat.
- **Multi-unit residential buildings (MURBs).** Upper floors of MURBs are found to have higher indoor temperatures (Touchie et al., 2016; Vardoulakis et al., 2015; Anderson et al., 2013) than other buildings in the same area. Furthermore, upper floors may limit the movement of vulnerable people to community cooling centers during heat waves (Touchie et al., 2016; Vellei et al., 2017; Lomas and Porritt, 2017).

Table 6. Air conditioning use in residential buildings per province based on the 2011 NRCan household survey (NRCan, 2011)

Province →	Canada	Atlantic	Quebec	Ontario	MB / SK	Alberta	BC
With AC	7,774,028	274,512	1,873,870	4,025,171	660,373	364,566	575,537
Without AC	5,682,397	681,934	1,438,216	1,020,066	219,458	1,072,295	1,250,428
Without AC (%)	42%	71%	43%	20%	25%	75%	68%

Table 7. Air conditioning use in residential buildings per building type based on the 2011 NRCan household survey (NRCan, 2011)

Building Type →	Single detached	Double row houses	Low-rise apartments	High-rise apartment
With AC	4,871,481	1,019,819	1,009,469	601,930
Without AC	3,273,293	701,747	1,029,173	388,931
Without AC (%)	40%	41%	50%	39%

7.3 The building occupants

Exposure to indoor heat events affect all categories of people of any ethnicity around the world. However, there are other factors related to occupants that would increase the risk of overheating. These include:

Vulnerability to heat. Vulnerability to heat weakens the physiological response of occupants and therefore shortens the safe exposure time. The list of people vulnerable to heat is presented in Section 5.

Activity level. Activity levels of occupants increase metabolic heat, and therefore increase body temperatures.

Clothing insulation. Thick and non-breathable clothing reduces body heat dissipation and therefore increases body temperatures.

Body rehydration. Lack of continuous body rehydration during heat exposure to replace sweat water loss increases the dehydration level of occupant body.

Adaptation to heat. Adaptation to warm temperatures with dry or humid conditions is an efficient measure to reduce body temperatures under heat conditions and therefore the overheating risk. People living in warm or humid climates naturally acquire adaptation to heat (Hajat and Kosatky, 2010). However, adaptation to heat in cold climates is limited in summer times (Basu, 2009; Medina-Ramon and Schwartz, 2007).

Mobility. Lack of occupant mobility to move around, change places, use ventilation fans to produce cooling effects, and opening windows for natural ventilation increases the risk of overheating in warm occupied spaces.

7.4 The community

Community factors that may increase the risk of overheating include:

- **Urban heat island (UHI)** effects which are present in large and dense cities. The temperature difference between cities and countryside may reach up to 12°C, particularly during the nighttime (Gachon et al., 2016), reducing, therefore, the effectiveness of nighttime ventilation cooling in buildings.
- **Urbanisation** a process that reduces green land spaces, spaces that are essential to cool the atmosphere and reduce UHI effects.

8 THE OUTDOOR ENVIRONMENT

8.1 Introduction

The conditions as prevail in the outdoors are the primary factor that influences overheating risk in buildings. Overheating risk is further exacerbated during extreme heat events in summer seasons. Many Canadian regions have experienced a high number of extreme heat events (HC, 2019). Some previous occurrences include a two-week long heat wave ending on July 17, 1936, with temperatures greater than 44°C. This heat wave was the longest and deadliest heat wave on record; it occurred in the provinces of Manitoba and Ontario, causing 1,180 mortalities (ECCC, 2017). A year later, on July 5, 1937, areas in Saskatchewan experienced the highest temperature ever recorded in Canada (ECCC, 2017). In the summer of 2005, Toronto experienced 41 hot days with peak temperatures of 34°C (ECCC, 2018a). In the summer of 2010 many cities in the province of Quebec suffered from higher temperatures than those occurring, on average, in July and August with daily maximum and minimum temperatures of 31-33°C, and 16-20°C respectively, over four to six days. The excess deaths rose above 1,360 for the province with about 383 in Montreal (Lebel et al., 2017). In the summer of 2009, British Columbia was struck by an eight day heat wave with peak temperatures of 34.4°C in Vancouver and excess mortality over 134 deaths (Kosatsky, 2010). It is expected that the future effects of climate change will increase the frequency and intensity of summer extreme heat events.

To be able to capture summer extreme heat events for overheating risk analysis, time-series of climate data are needed for a sufficiently long time period. Local climate data may be available from long observational records from the past decades. However, for future climate change projections, climate data can only be estimated. The simplest estimation method uses the morphing methodology in which the present-day observed data are combined with the monthly temperature averages obtained from climate modelling studies for given climate change scenarios to produce hourly time series data (Belcher et al., 2005). The second method uses an aggregate of global climate models to simulate the coupled land-atmosphere-ocean system based on certain assumptions of future climate change in terms of radiative forcing scenarios (RCP = 2.6 to 8.5 W/m^2; IPCC, 2014).

This section presents methodologies to: (1) obtain reference climate data of selected Canadian locations for the historical period and future climate projections; (2) define and characterise climate extreme heat events; and (3) extract climate extreme heat events and extreme summer years for overheating risk analysis through completion of thermal simulations of buildings. The methodology to extract extreme heat events is applied to develop spatial heat maps for selected Canadian locations.

8.2 Climate change effects

The effects of climate change have been detected in Canada. Observational records convey that the average temperatures across Canada have increased by 1.3 ºC over the past 50 years, approximately twice the average increase recorded globally (Bizikova et al. 2008). The degree of warming has been found to vary spatially, temporally, and for different climate indices.

Stronger increases have been recorded for daily minimum temperatures than for daily maximum temperatures, in the north-western and western regions of Canada than the rest of the country, and in the winter and spring seasons than the rest of the year (Zhang et al. 2000).

Future climate projections are expected to influence considerable changes in temperature patterns across Canada. The time-series of long-term temperature forecasts made by the Coupled Model Inter-comparison Project Phase 5 (CMIP5) models provided by ECCC (2016) suggests a median warming of approximately 2 ºC to 6 ºC in average temperatures across Canada for different scenarios as shown in Figure 14. The future trajectories of temperature have been forecasted for three scenarios: RCP 2.6, RCP 4.5, and RCP 8.5 for the time-periods spanning 20th and 21st centuries. The projected changes vary spatially, and across different provinces of Canada.

Table 8 summarises the projected changes in annual average temperatures across Canada for two extreme scenarios: RCP 2.6 and RCP 8.5. The provinces projected with warming magnitudes higher than the Canadian average are highlighted in red. The provinces of Nunavut, Northwest Territories, and Manitoba are consistently projected with significantly higher warming under all RCPs than the rest of the Canada. The provinces of Saskatchewan and Yukon Territory also fall marginally above the Canadian average in terms of the projected warming.

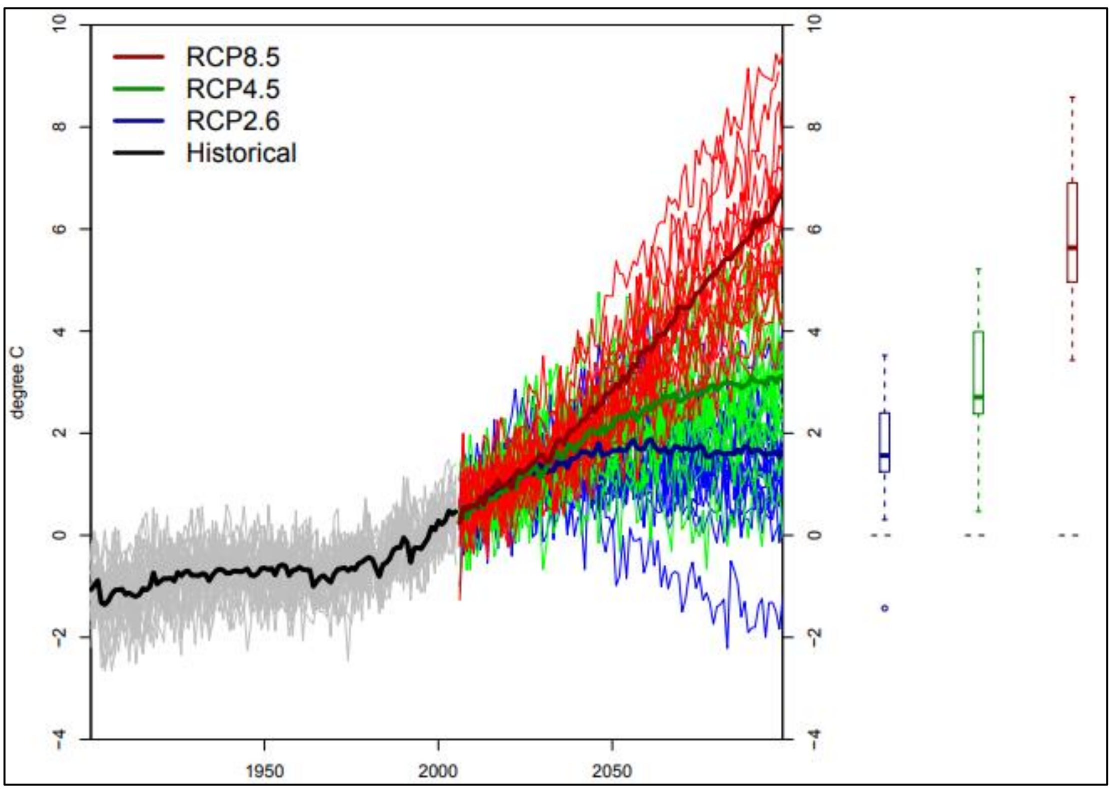


Figure 14. Time-series of projected changes in annual mean temperatures in Canada. The changes were calculated with reference to a baseline time-period of 1986-2005 (Source: http://climate-scenarios.canada.ca/index.php?page=download-cmip5)

Table 8. Projected median changes in average temperatures for individual provinces, and averaged across Canada*

Region	RCP 2.6, (˚C)		RCP 8.5, (˚C)	
	2050s	2090s	2050s	2090s
Canada	1.8	1.8	3.5	6.3
Alberta	1.6	1.7	3.2	5.8
British Columbia	1.5	1.6	2.9	5.2
Manitoba	1.9	2.0	3.9	7.1
New Brunswick	1.6	1.6	3.1	5.4
Newfoundland & Labrador	1.5	1.5	3.0	5.4
Northwest Territories	2.3	2.3	4.5	8.4
Nova Scotia	1.5	1.5	2.8	4.9
Nunavut	2.3	2.2	4.7	8.7
Ontario	1.7	1.7	3.5	6.3
Prince Edward Island	1.6	1.6	3.0	5.2
Quebec	1.7	1.7	3.5	6.3
Saskatchewan	1.8	1.9	3.6	6.5

*Changes corresponding to RCP 2.6 and RCP 8.5 were provided for 2050s (2046-2065) and 2090s (2081-2100) timelines; Changes were calculated with reference to a baseline historical time-period of 1986-2005 Source: http://climate-scenarios.canada.ca/index.php?page=download-cmip5

8.3 Reference climate data

Eleven representative Canadian cities are selected to produce the reference climate data. The reference climate data includes both the historical observation data and climate modelling data for future projected climates. More details on the methodology to extract those climate data are found in Gaur et al. (2018). A brief description of the methodology follows.

8.3.1 Reference climate data for the historical period

The reference historical observation climate data spanning the period of 1986-2016 (31 years) are taken from the observation climate database maintained by ECCC (2018b). The climate variables include the hourly observations of the global horizontal solar irradiance, total cloud-cover, relative humidity, air temperature, rainfall, atmospheric pressure, wind speed and direction, and snow-depth. The climate data are collected from all the weather stations within a city domain and then averaged to produce a single weather file for the selected city. The global horizontal solar irradiance is split into its direct beam and diffuse components using the method of Orgill and Hollands (1977). The data gaps in the averaged weather data files of cities are filled-in using bias-corrected data taken from the Climate Forecast System Reanalysis (CFSR) databases (Saha et al., 2010).

8.3.2 Reference climate data for future climate projections

The climate modelling data covering the period 1950 to 2100 were taken from the climate databases of ECCC (2018b). The ECCC's data were obtained using the CanESM2 Large

Ensemble (LE) simulation model. CanESM2 LE is a Global Climate Model (GCM) with five ensemble members. The simulations were performed with a space resolution of 2.8°, and 10 randomly selected sets of cloud physics parameterizations (Arora et al., 2011). A total of 50 simulations were produced. To dynamically downscale the CanESM2 LE to a 0.44° grid, regional simulations were performed using the CanRCM4 model (Scinocca et al., 2016). A sub set of the CanRCM4 simulations, comprising of 15 realizations (runs), were archived in hourly time-steps by ECCC and acquired by the National Research Council (NRC) for the purpose of conducting research related to buildings. The covered climate variables include: global solar irradiance, temperature, relative humidity, wind speed and direction, atmospheric pressure and snow cover. The climate data were grouped into data sets of 31 years, including the historical period 1986-2016 and seven future time-periods coincident with the globally averaged future warming scenarios of 0.5°C, 1.0°C, 1.5°C, 2.0°C, 2.5°C, 3.0°C, and 3.5°C. An analysis of the CanRCM4 simulations indicated that the above prescribed levels of future global warming scenarios would be reached in the future over the 31-year time-periods of 2001-2031, 2013-2043, 2024-2054, 2034–2064, 2044-2074, 2053-2083, and 2062–2092, respectively. As such, the 15 members of the hourly CanESM2 LE projections covering the aforementioned historical and future time-periods were extracted for the selected Canadian cities for the generation of historical and projected time-series of the climate variables. The acquired raw data of the CanRCM4 simulations were bias-corrected by comparing the simulated data of each climate variable with the city-averaged observation data for the historical period. Bias-correction factors were thus developed for each hour and each month in each city and then applied to the simulation raw data for both the historical and future climate projections.

8.3.3 Accuracy of the climate modelling data

Studies have found that the regional simulated climate data for the historical and future climate projections are associated with biases (Gaur et al. 2018). Therefore, the simulated data need to be bias-corrected using observation data. Since climate observation data is not available for each grid point of the simulated climate data, any bias correction method will still carry on some biases. Comparing the NRC bias-corrected climate data with historical observation data in the selected cities showed that the simulated climate data are warmer by several degrees Celsius than those from observations. The annual maximum temperature of the observation data is compared with the simulation data in Table 9, over the historical period (1986-2016) for eleven major Canadian cities. The deviation of the simulated maximum temperature depends on the city location and ranges from a minimum value of -4.9 to 6.3°C to a maximum value of -1.9 to 11.2°C. For example, for Ottawa, Ontario, the deviation of the maximum temperatures varies between 2.3 to 5°C. Vancouver (BC) shows the highest deviation from 6.3 to 11.2°C. St. John's, shows, however, negative deviations. In this regard, the significant temperature deviation of the simulated climate data portrays the fact that assessing climate change impacts on buildings in terms of relative changes to the reference historical period is recommended as compared to using the absolute changes, which may not be representative of future climate impacts.

Table 9: Comparison between simulation and observation data for the annual maximum temperature for the historical time frame 1986–2016 in eleven Canadian cities.

City	T_{max} Observed	Min. T_{max} (Simulation)	|ΔT|	Max. T_{max} (Simulation)	|ΔT|
Ottawa	**36.6**	**38.9**	**2.3**	**41.6**	**5.0**
Toronto	**37.0**	**37.0**	**0.1**	**40.5**	**3.6**
Montreal	**35.1**	**38.1**	**3.0**	**41.4**	**6.3**
Halifax	**32.9**	**33.0**	**0.1**	**35.7**	**2.8**
St. John's	**28.8**	**23.9**	**-4.9**	**26.8**	**-1.9**
Charlottetown	**32.4**	**32.2**	**0.1**	**35.4**	**3.1**
Moncton	**34.7**	**35.9**	**1.2**	**38.9**	**4.2**
Winnipeg	**37.9**	**39.3**	**1.4**	**42.3**	**4.4**
Saskatoon	**40.4**	**37.6**	**-2.8**	**40.2**	**0.2**
Calgary	**34.0**	**35.6**	**1.6**	**39.8**	**5.8**
Vancouver	**30.0**	**36.3**	**6.3**	**41.2**	**11.2**

8.4 Definition of extreme heat events

Extreme heat events, EHE (also dubbed heat waves) are the result of natural variability of climate exacerbated by global climate warming (IPCC, 2014). From the climate perspective, an EHE is vaguely defined as a rare event that occurs at a particular place over a particular period of time (IPCC, 2014; NASEM, 2016). However, for practical applications there is no specific and universal definition of EHE (WHO, 2009; Gachon et al., 2016; EPA, 2016). Environment and Climate Change Canada (ECCC) uses *Humidex* combined with the daily maximum and minimum temperatures to define local EHEs (ECCC, 2018a) to issue public heat warnings in various provincial regions (Table 11) are close to the minimum values of the daily outdoor temperatures used in ECCC's public heat alert warnings (Table 10). However, this definition does not account for other climate variables (e.g., solar radiation, wind speed, etc.) that are important for overheating risk analysis in buildings. From the building and occupant comfort perspective, a new definition has been developed, and is used in this guideline document where EHEs are treated in a similar way as indoor overheating events but with different SET thresholds.

An outdoor *extreme heat event* is defined as **continuous *daily outdoor heat events with warm temperatures* that affect the comfort of people outdoors who are directly exposed to such heat events under sunshade and over at least one day**.

A daily outdoor heat event is defined as a heat event with warm temperatures that occurs daily over at least a prescribed number of hours during daytime and triggers a physiological response and action of people under its direct exposure to restore thermal comfort. Multiple EHEs are declared, if they are separated by a recovery period of at least one day.

During a whole day exposure, people may perform various activities when in outdoor and indoor environments. During daytime, people are assumed walking outdoors under sun shade whilst during nighttime they are assumed sleeping. The magnitude of an outdoor EHE duration, N, (days) is expressed in a similar way as indoor overheating events, but with different threshold values for the outdoor comfort and sleep during nighttime. Equations (1) to (3) hold for EHE. However, the hourly values of t-SET are calculated using the climate variables (temperature, relative humidity, and wind speed). The solar radiation under shade (direct beam radiation is excluded) is converted to a mean radiant temperature using the formulation of Pickup and de Dear (2000) and ASHRAE (2017). More details may be found in Laouadi et al. (2020a). The threshold value of t-SET during daytime exposure is fixed at SET_d = 30°C (31.2°C for acclimatized people). People are assumed not acclimatized during the first month of expected heat events in the summer season, which is set to May for Canadian locations. For other summer months, people are assumed acclimatized to heat events from June to September (for the Canadian locations).

During nighttime when people are asleep, the relationship between the indoor conditions with the outdoor is not known. Therefore, to quantify the direct effect of the outdoor thermal conditions on a person's sleep, the reference value of SET_n for sleep is assumed to correspond to the lower temperature value of the adaptive thermal comfort range for the location under consideration. The rationale behind this selection is that: (1) people residing in indoor environments are more tolerant to heat in naturally ventilated buildings; (2) the indoor temperature is usually higher by several degrees Celsius than the outdoor temperature during nighttime; and (3) most people prefer to cover-up and thus endure cooler temperatures when sleeping (Lin and Deng, 2008a,b). The corresponding t-SET values are calculated for people in a sleeping state (metabolic rate = 0.7 met) with sleepwear insulation value of 1.57 clo (long top and bottom pyjama, sleepers, laying on a mattress; Lin and Deng, 2008b), air velocity of 0.15 m/s and relative humidity of 50%. Table 11 lists the calculated values of SET_n for selected Canadian cities. The average monthly temperatures (T_{ma}) for the period 1981-2010 are taken from the ECCC (2018a). The lower temperature limits of the adaptive thermal comfort range (T_{CL}) are calculated according to the ASHRAE 55 standard (ASHRAE, 2017). It should be noted that the values of the adaptive comfort temperature (T_{CL}) in Table 11 are close to the minimum values of the daily outdoor temperature used in ECCC's public heat alert warnings (Table 10).

Table 10. ECCC's heat alert criteria for public warnings (T_{max} and T_{min} are daily maximum and minimum temperatures, respectively)

Climate Region	Definition of extreme heat events
Newfoundland and Labrador; New Brunswick; Nova Scotia; and Prince Edward Island	Humidex or T_{max} ≥ 40°C over more than 1 hour
Quebec, except Nunavik	Humidex ≥ 40°C, and T_{max} ≥ 30°C over more than 1 hour; or T_{max} ≥ 40°C
Ontario - extreme southwest (Essex and Chatham-Kent Counties)	T_{max} ≥ 31°C over two or more days, and T_{min} ≥ 21°C; or Humidex ≥ 42°C over two or more days
Ontario - remainder of southern Ontario (including the District of Parry Sound)	T_{max} ≥ 31°C and T_{min} ≥ 20°C over two or more days; or Humidex ≥ 40°C over two or more days
Ontario - North	T_{max} ≥ 29°C and T_{min} ≥ 18°C over two or more days; or Humidex ≥ 36°C over two or more days
Manitoba - South	T_{max} ≥ 32°C and T_{min} ≥ 16°C over two or more days; or Humidex ≥ 38°C over two or more days
Manitoba - North	T_{max} ≥ 29°C and T_{min} ≥ 16°C over two or more days; or Humidex ≥ 34°C over two or more days
Saskatchewan - South (excluding Meadow Lake, The Battlefords, Prince Albert, and Hudson Bay)	T_{max} ≥ 32°C and T_{min} ≥ 16°C over two or more days; or Humidex ≥ 38°C over two or more days
Saskatchewan - North and Central (including Meadow Lake, The Battlefords, Prince Albert, and Hudson Bay)	T_{max} ≥ 29°C and T_{min} ≥ 14°C over two or more days; or Humidex ≥ 34°C over two or more days
Alberta - Extreme south (includes Pincher Creek, Cardston, Lethbridge, Medicine Hat)	T_{max} ≥ 32°C and T_{min} ≥ 16°C over two or more days
Alberta - Remainder of Alberta (includes Cities of Edmonton, Red Deer and Calgary)	T_{max} ≥ 29°C and T_{min} ≥ 14°C over two or more days
British Columbia - Metro Vancouver, Fraser Valley, Howe Sound, Whistler, Sunshine Coast only.	Today's average temperature at 14:00 and tomorrow's forecast T_{max} ≥ 29°C at Vancouver International Airport; or Today's average temperature at 14:00 and tomorrow's forecast T_{max} ≥ 34°C at Abbotsford Airport.
Northwest Territories and Nunavut	Humidex or T_{max} ≥ 40°C

Table 11. Reference values of SET_n for sleep for selected Canadian cities.

City	May			Jun.			Jul.			Aug.			Sep.		
	T_{ma}	T_{CL}	SET_n	T_{ma}	T_{CL}	SET_n	T_{ma}	T_{CL}	SET_n	T_{ma}	T_{CL}	SET_n	T_{ma}	T_{CL}	SET_n
St John's, NF	6.4	16.3	21.1	10.9	17.7	22.2	15.8	19.2	23.4	15.8	16.1	23.5	12.4	18.1	22.6
Charlotte-town, PEI	9.2	17.2	21.8	14.5	18.8	23.1	18.7	20.1	24.2	18.7	18.3	24.1	14.1	18.7	23.0
Halifax, NS	10.1	17.4	22.0	15.2	19.0	23.3	18.8	20.1	24.2	18.8	19.1	24.3	15.5	19.1	23.4
Moncton, NB	10.7	17.6	22.2	16.0	19.3	23.5	19.5	20.3	24.3	19.5	19.0	24.3	14.5	18.8	23.1
Montreal, PQ	12.4	18.1	22.6	17.4	19.7	23.9	19.8	20.4	24.4	19.8	18.7	24.2	14.1	18.7	23.0
Ottawa, ON	13.5	18.5	22.9	18.7	20.1	24.2	21.2	20.9	24.8	21.2	19.9	24.5	15.3	19.0	23.3
Toronto, ON	14.1	18.7	23.1	19.4	20.3	24.3	22.3	21.2	25.1	22.3	21.5	24.9	17.2	19.6	23.8
Winnipeg, MB	11.6	17.9	22.4	17	19.6	23.8	19.7	20.4	24.4	19.7	18.8	24.2	12.7	18.2	22.6
Saskatoon, SK	11.8	18.0	22.5	16.1	19.3	23.5	19	20.2	24.3	19	18.2	24.0	12.0	18.0	22.5
Calgary, AB	9.7	17.3	21.9	13.7	18.5	22.9	16.5	19.4	23.6	15.8	19.2	23.4	11.0	17.7	22.2
Vancouver, BC	12.8	18.3	22.7	15.7	19.2	23.4	18	19.9	24	18	19.9	24.0	14.9	18.9	23.2

8.5 Characterizing extreme heat events

Similar to indoor overheating events, outdoor EHE's are characterized by three attributes:

Duration, measured in terms of the number of days of continuous daily outdoor heat events.

Severity, measured in (°C·h) and indicates the magnitude of EHE as given by equation (1) evaluated under the outdoor conditions

Intensity, measured in (°C) and calculated as the ratio of severity to duration (in hours).

As per this definition, many types of EHEs during the summer season may occur. Three major types are distinguished: long, intense and severe. Other combinations are also possible such as long and intense, long and severe, or intense and severe.

8.6 Procedure to extract extreme summer weather years

Following the approach of Laouadi et al. (2020a), extreme heat events with their associated extreme reference summer weather years (RSWY) are extracted from a data set of 31 years of climate data to capture all types of extreme heat events for the historical period (1986-2016) and future time-periods of climate projections. The summer period is fixed from May to September. The procedure to extract such extreme heat events and their associated RSWY is a follows:

1. Extreme heat events (or heat waves) for each year of a 31 year period are identified based on equations (1) to (3) and sorted in a descending order by their values for duration, intensity, and severity. These maximum values of heat wave characteristics are assigned to each year of the 31 year data set;
2. The return period of heat waves is fixed to 15.5 years, which corresponds to the second extreme year of 31 years;
3. The cumulative frequency distribution of the maximum values of duration, intensity and severity are plotted and fitted with suitable distribution functions (using statistical tools) such as the generalized extreme value distribution (GEV), Gumbel distribution, or any other suitable function (Note: There is no single function that satisfies all the maximum value distributions). The extreme years are then chosen if their calculated return periods are close to the chosen value of 15.5 years. In most cases, the extreme years are those ranked second by their maximum values for duration, intensity and severity. If the first ranked years have the same frequency values or are very close, the one with the highest severity value is chosen to represent the second extreme year. Similarly, if the second ranked extreme years have the same frequency values, the one with the highest severity value is chosen.

Table 12 lists the obtained RSWY with extreme heat waves using the historical climate observation data for the period of 1986-2016 in the selected Canadian cities.

Table 12. RSWY with three types of extreme heat waves for the historical period (1986-2016) in the selected Canadian cities.

City	Extremely long heat waves	Extremely intense heat waves	Extremely severe heat waves
St John's, NF	1990	1990	1990
Charlottetown, PEI	2002	2002	2002
Halifax, NS	1988	1988	1988
Moncton, NB	1997	2013	2002
Montreal, PQ	2010	2010	1987
Ottawa, ON	2010	2006	2010
Toronto, ON	1987	2006	2011
Winnipeg, MB	2005	2007	1995
Saskatoon, SK	2002	1988	1988
Calgary, AB	2007	2007	2007
Vancouver, BC	1989	1989	1989

8.7 Heat wave maps for outdoor exposure

The foregoing procedure to extract extreme heat waves from 31 years of climate data is used as well to develop spatial heat wave maps for outdoor exposure for selected Canadian cities. These heat wave maps are very important to identify locations with potential risk to the human health, and for future planning of heat alert intervention in those locations. For the historical observation data set (1986-2016), the duration, intensity and severity values of extreme heat waves and extreme annual number of heat waves are plotted in their absolute values to produce heat wave maps for the selected Canadian locations. The average values of duration, intensity, and severity of all summer heat waves for the entire time frame are also plotted. However, for the simulated climate data sets of future climate projections, the extreme heat waves are calculated for each run of the 15 runs and then the heat wave values are averaged over the 15 runs. The 15 run average results for the heat wave maps are presented in terms of the percentage increase over the simulated historical time frame period (1986-2016). More details on this topic may found in Laouadi et al. (2020c).

8.7.1 Historical observation period

Figure 15 shows the heat exposure maps in terms of duration, intensity, and severity indices of extreme heat waves and the annual number of summer heat waves for the historical observation climate data. Figure 16 shows the plots of the average values of all summer heat waves for the entire time frame period (1986-2016). The results show that the cities of Ottawa, Toronto, Montreal, and Winnipeg are currently under higher extreme heat than other cities. For those cities, the severity and intensity indices of heat waves are quite high, and therefore people under outdoor exposure should constantly drink water to rehydrate themselves and should not stay for long period of time (> 4 hours) to avoid any heat-related health issues.

8.7.2 Future climate projections

Figure 17 and Figure 18 show the maps of heat waves for the future climate projection for the mid-century global warming GW2.0°C (2034-2064). Compared to the historical period (Figure 15 and Figure 16), heat waves are longer, and more intense and severe. In terms of the severity of extreme heat waves, the biggest change is noticed in Calgary where the severity index is increased by more than 600% (with respect to the simulated historical period), followed by Toronto and St. John's (> 527%), Charlottetown (> 463%), Saskatoon (> 357%), Vancouver (> 296%), Halifax and Moncton (>247%), and Ottawa, Montreal, and Winnipeg (> 157%). Similarly, the duration and intensity of extreme heat waves are increased by 82% (Winnipeg) to 400% (St. John's), and 31% (Montreal) to 515% (St. John's), respectively. However, the changes in the average values of the heat wave characteristics for the entire climate period are less dramatic than the extreme values. The changes in the average duration, intensity and severity indices range from 4% (St. John's) to 59% (Toronto), 49%(Ottawa) to 97% (Halifax), and 64%(St. John's) to 212% (Toronto), respectively.

Figure 19 and Figure 20 show the maps of heat waves for the future climate projection at the end of the 21st century with a global warming GW 3.0°C (2053-2083). The trend is similar to the mid-century projections with heat waves becoming longer, and more intense and severe. In terms of the severity of extreme heat waves, the biggest change is noticed in Charlottetown where the severity index is increased by more than 1700%, followed by Calgary and St. John's (> 1412%), Toronto (> 1223%), Saskatoon, Moncton, Halifax, and Vancouver (> 583%), and Montreal, Ottawa, and Winnipeg (> 268%). Similarly, the duration and intensity of extreme heat waves are increased by 130% (Winnipeg) to 489% (Charlottetown), and 47% (Montreal) to 1315% (St. John's), respectively. However, the changes in the average values of the heat wave characteristics for the entire climate period are less dramatic than the extreme values. The changes in the average duration, intensity and severity indices range from 8% (St. John's) to 127% (Toronto), 78%(Winnipeg) to 168% (Charlottetown), and 151%(St. John's) to 525% (Toronto), respectively.

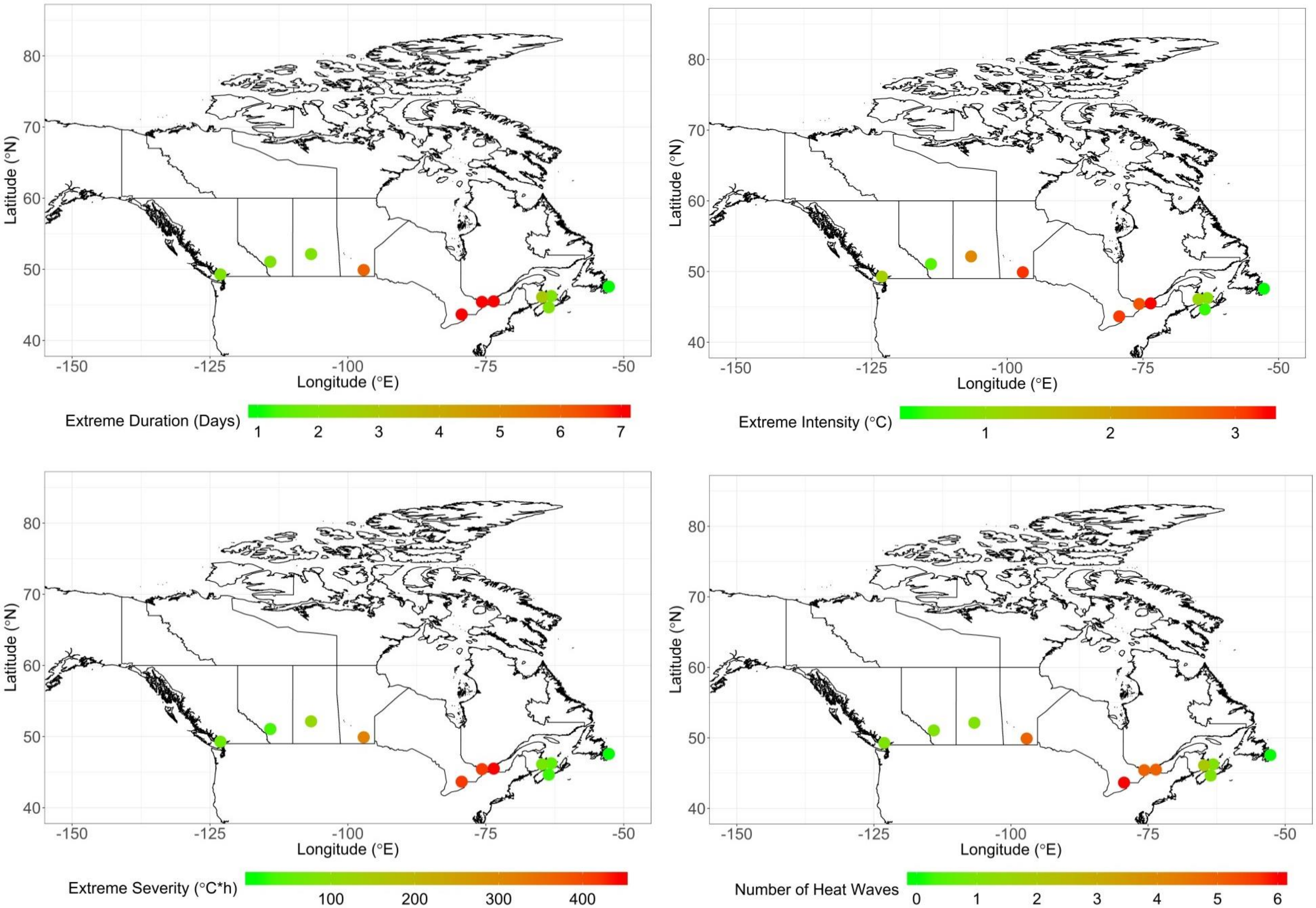


Figure 15: Maps of extreme heat wave characteristics for historical observed climate data

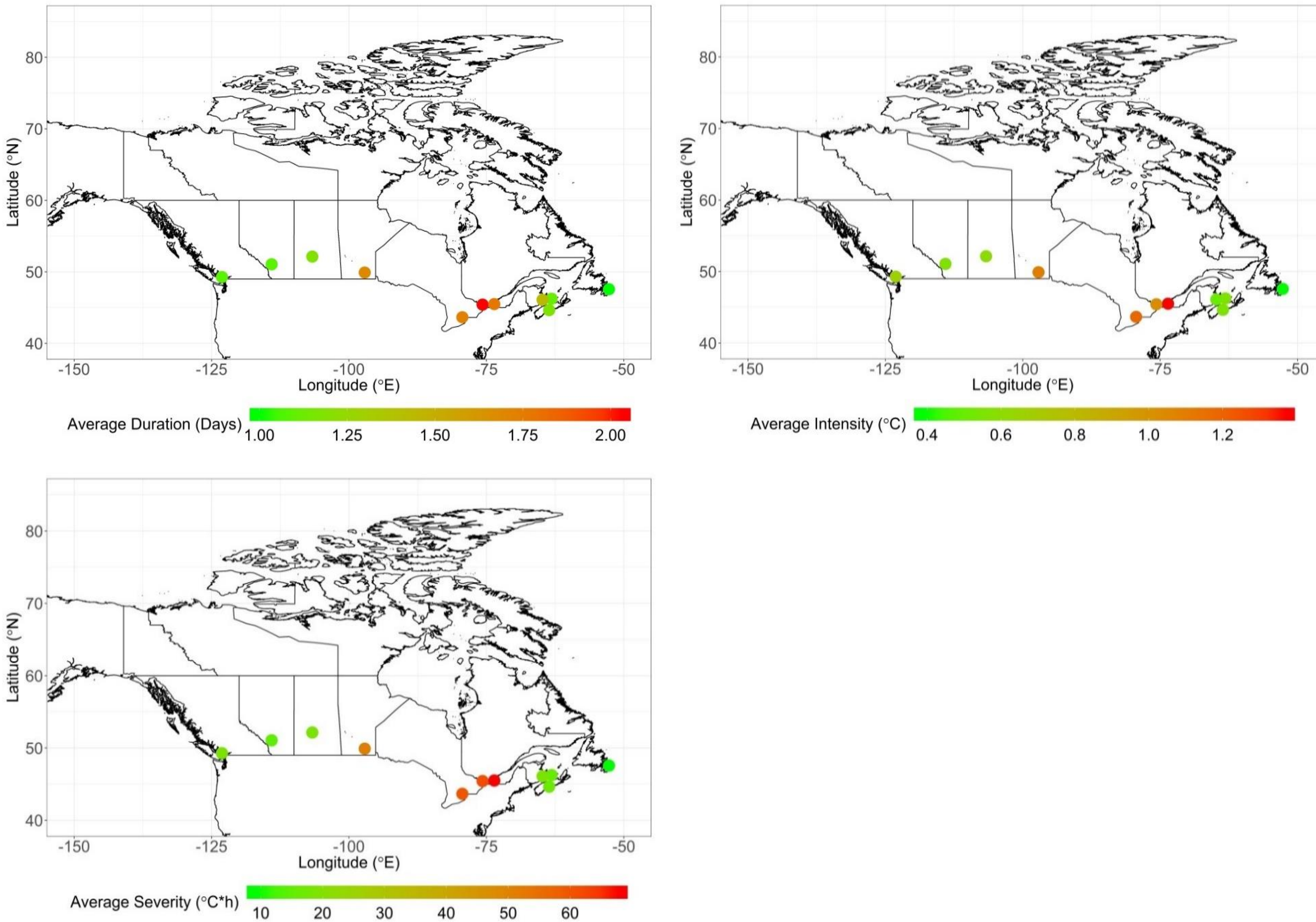


Figure 16: Maps of average characteristics of all heat waves for historical observed climate data

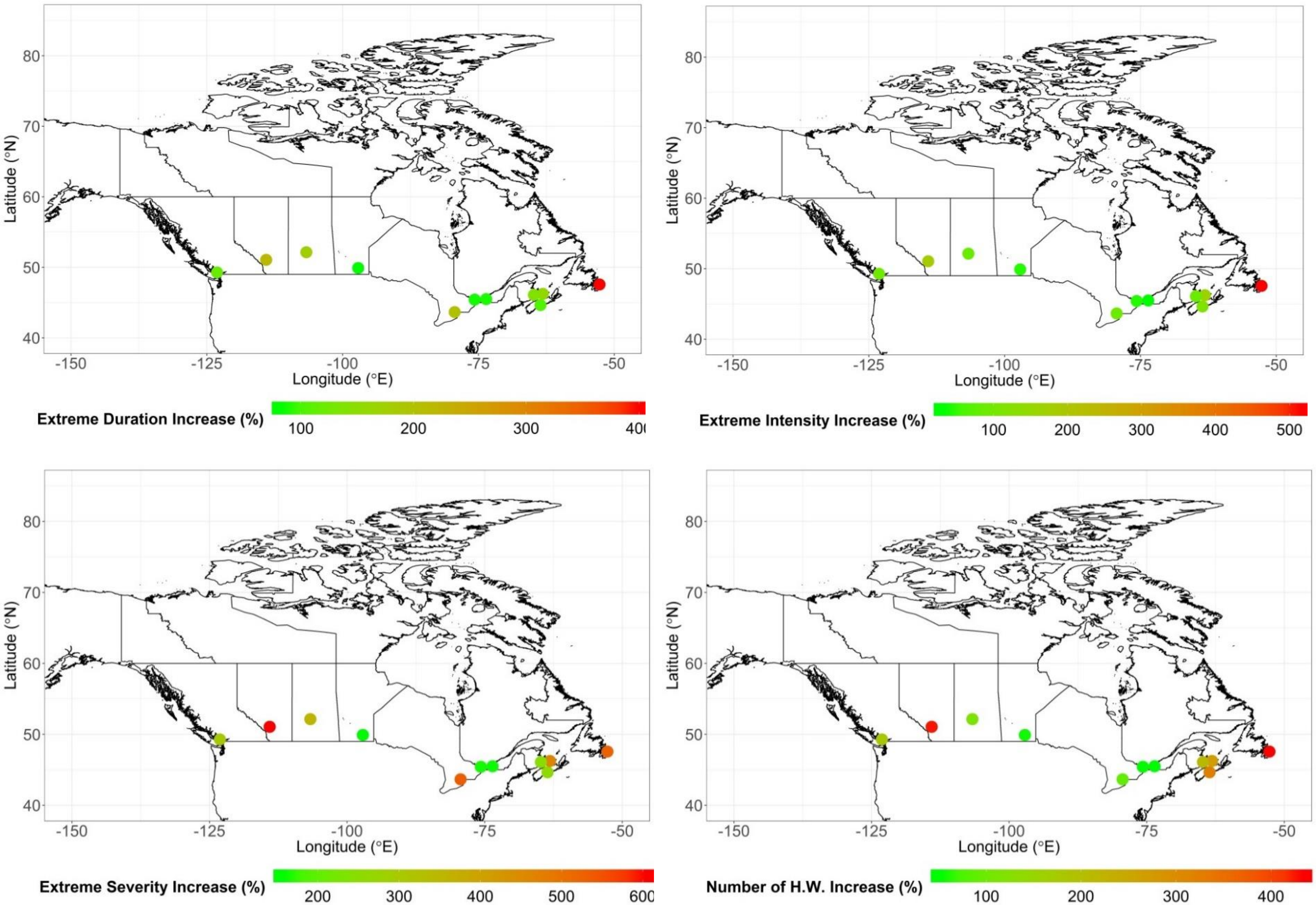


Figure 17: Maps of relative change (%) in extreme heat wave characteristics for future climate projection: GW2.0°C (2034-2064)

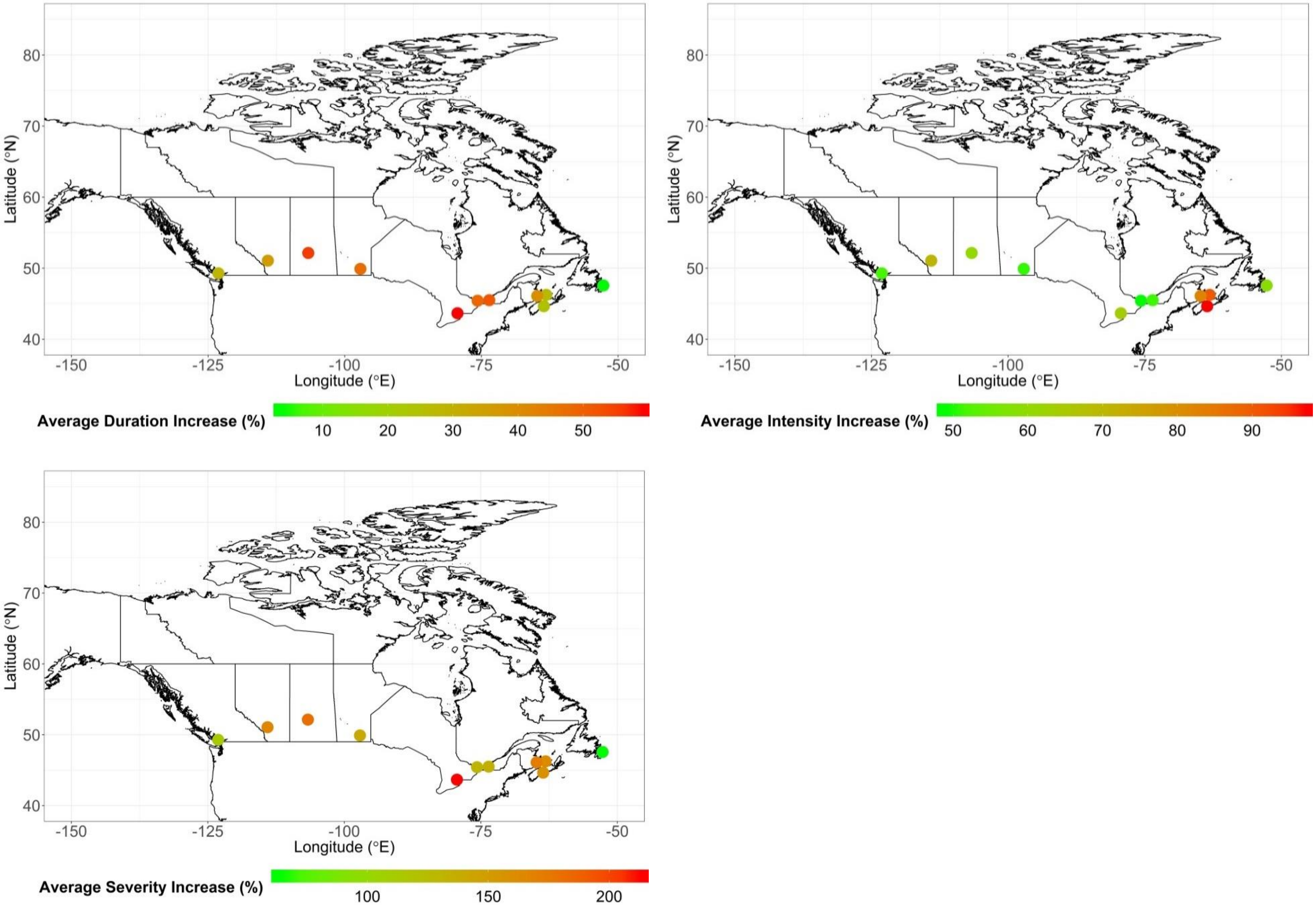


Figure 18: Maps of relative change (%) in average characteristics of all heat waves for future climate projection: GW2.0°C (2034-2064)

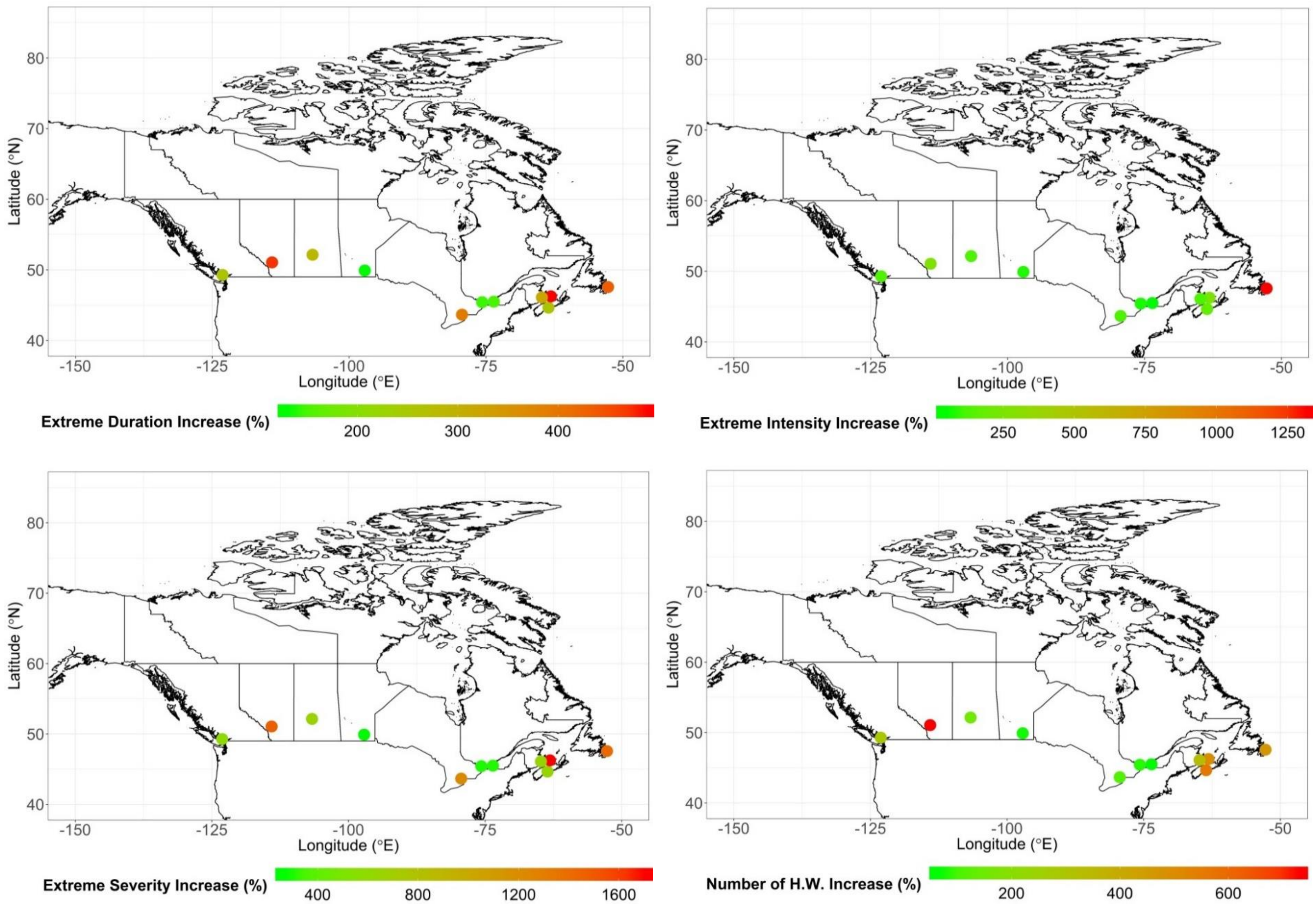


Figure 19: Maps of relative change (%) in extreme heat wave characteristics for future climate projection: GW3.0°C (2053-2083)

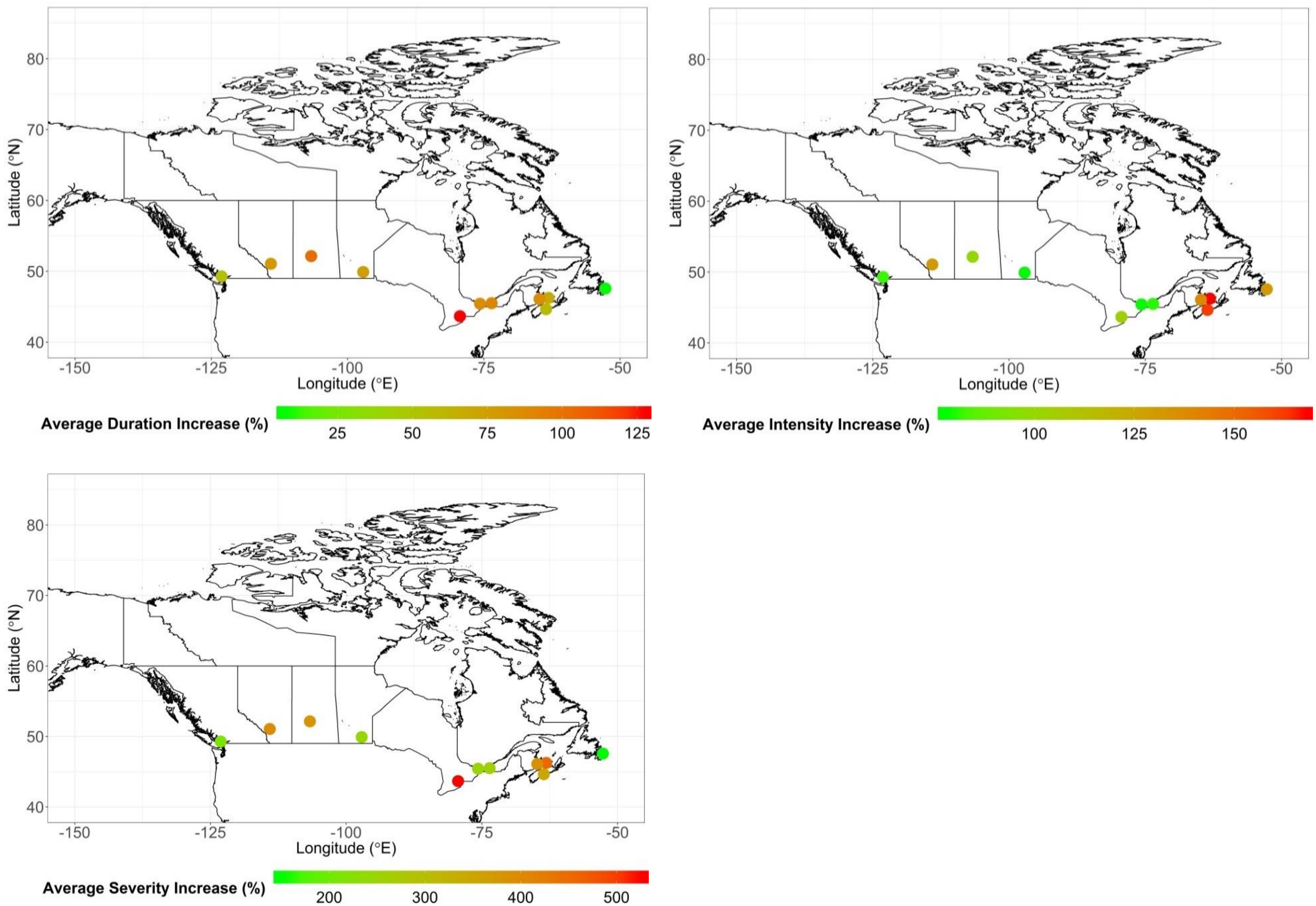


Figure 20: Maps of the relative changes (%) in the average characteristics of all heat waves for the future climate projection: GW3.0°C (2053-2083)

9 Evaluation of Overheating

This section presents the procedure and requirement to evaluate overheating risk in buildings

9.1 Evaluation procedure

Overheating in buildings can be evaluated through the use of either building computer simulation or continuous field monitoring of the indoor conditions during the summer period. The procedure for building computer simulation consists of the following steps:

1. Develop a building simulation model. The building space should be zoned to have separate thermal zones during daytime and nighttime occupancies. Thermal zones should be associated with the spaces that are occupied by the same group of occupants during a complete day of exposure. For example, in residential buildings, occupants dwell in living rooms during the daytime and sleep in bedrooms during nighttime. The living room and bedroom are then zoned as two different thermal spaces.
2. For a given geographical location, extract the reference summer weather years (RSWY) covering the three types of extreme heat events (long, intense, severe) using the procedure in Laouadi et al. (2020a) and Section 8. Other types of summer weather data suitable for overheating analysis may be used as well.
3. Compute the building indoor conditions for the entire year or summer season (air temperature, mean radiant temperature, relative humidity, air velocity) using one type of RSWY of Step 2.
4. Post process the simulation results to compute the hourly values of t-SET of each occupied thermal zone of building using the reference occupant data given in Table 5.
5. Evaluate equations (1) to (3) and determine all possible overheating events for each group of spaces occupied by the same occupants during day and night times (e.g., living room and bedrooms) for the entire summer period, and calculate the severity and intensity indices (from equations 1 to 3).
6. For each group of occupied spaces (with the same occupants), select the extreme overheating events (from Step 5) that have the highest severity and intensity values.
7. Apply the overheating criteria to those extreme (intense and severe) overheating events of Step 6 to determine whether an overheating event has occurred, given that either the intensity or the severity value exceeds the threshold limits as previously specified in Figure 10 to Figure 13.
8. Apply steps 3 to 7 to any additional type of RSWY for the location under consideration.
9. Overheating is declared in the building, if the overheating criteria are satisfied for any type of RSWY used for the location under consideration.

The foregoing procedure can also be used with continuous field monitoring or forecasting of local weather conditions in the summertime. In this case, the extreme weather data of Step 2 are to be replaced by the monitored or forecasted weather data at the building location. Similarly, if the field monitoring also includes the indoor conditions, the computed indoor conditions of Step 3 will have to be replaced by the measured indoor conditions to evaluate overheating.

9.2 Requirements for computer simulation

9.2.1 Simulation software

The simulation software to evaluate overheating in buildings should have the following capabilities:

- Use local hourly (or sub hourly) weather data for an entire year or summer period. The weather data should include temperature, relative humidity, solar radiation (diffuse and global), and wind speed and direction;
- Treat building spaces as multiple thermal zones;
- Model natural ventilation using air flow networks or other suitable method;
- Produce hourly (or sub hourly) data of the indoor conditions used for overheating analysis

9.2.2 Building simulation model

Archetypical (generalized) building models can be used to conduct general overheating analysis in selected building types such as residential buildings, schools, offices, etc. Models of real buildings can also be used to analyze overheating in specific buildings.

9.2.3 Calibration of building simulation model

Building simulation models should be calibrated before conducting overheating analysis. Calibration involves adjusting selected key simulation inputs to minimize the error between simulation data and benchmark case. Approaches for building calibration can be grouped into accuracy levels: simple, intermediate and detailed. The simple approach consists of comparing the annual energy intensity for heating, cooling and total energy of the simulation model with published data for similar buildings in the same location. This approach is used with archetypical (generalized) building models for which no real measurement data are available. The intermediate approach compares the hourly or monthly energy demand for electricity and gas of the building simulation model with the metered energy data in real buildings. This is true for the case where the building simulation model is a representation of a real building. The metered energy data may be retrieved from the energy meters of the real building or from local utility companies. The outdoor weather data at the building site should be available (measured locally or taken from nearby airport data) to conduct building simulation for the period over which a comparison is being made. ASHRAE Guideline 14 (2014) should be used to conduct energy metering in real buildings and for the calibration of a building simulation model. The detailed approach compares both hourly energy demand for electricity and gas and indoor temperatures of the simulation model with the monitored data from the real building. This is the case where the building simulation model is a representation of a real building. The outdoor and indoor conditions of the real building should be monitored and available during the data comparison period.

9.3 Field monitoring

Field monitoring may include monitoring of the outdoor environment, or the indoor environment, or both. Monitoring the outdoor environment (similar to forecasting of the outdoor weather) is treated in a similar way as in the above building simulation method. Monitoring of the indoor conditions alone or combined with the outdoor conditions follows directions given in the next sections.

9.3.1 Measurement protocol

The measurement protocol should include the following variables:

- Indoor average temperature of each thermal zone of building;
- Indoor average relative humidity of each thermal zone of building;
- Indoor mean radiant (or globe) temperature of each thermal zone of building, measured at the occupant position in the space at a seating height (1.1 m above floor) according to ASHRAE-55 (2017);
- Indoor average air velocity of each thermal zone of building, measured at the occupant position in the space at a seating height (1.1 m above floor) according to ASHRAE-55 (2017);
- Occupant type (young or older adults) of each occupied building space;
- Typical clothing worn during daytime and nighttime (during sleeping) over the monitoring period;
- Activity level of occupants during daytime over the monitoring period.
- Outdoor temperature and relative humidity (**optional**) at building site, measured at a point far away from building influence (e.g., at a sufficient height above roof surfaces of neighboring buildings);
- Wind speed and direction (**optional**) at building site, measured at a height of 10 m in free air stream, or at a point far away from building influence;
- Outdoor solar radiation (diffuse and global) (**optional**) at building site, measured at a point far away from building influence. Neighboring airport data may be used as well.

It should be noted that the optional quantities in the above protocol are used for information purpose, or to calibrate a building simulation model representing a real building. Measurement of both outdoor and indoor conditions are often used to validate or calibrate a building simulation model to further conduct overheating analysis in other locations or using different weather data.

9.3.2 Thermal zoning of occupied spaces

Monitored building interior spaces should be separated into thermal zones according to occupant usage of the building spaces during a complete day exposure. If building spaces occupied during daytime are different from the ones occupied during nighttime for sleeping, they should be treated as different thermal zones. If occupants use various spaces during daytime, those spaces should be treated as different thermal zones as well. All spaces occupied by a same group of occupants during a complete day of exposure are used to carry out an overheating analysis.

10 MITIGATION MEASURES TO REDUCE OVERHEATING RISK

Mitigation measures that can potentially reduce overheating risk in buildings are listed below. However, prevention of overheating may necessitate applying a combination of measures.

10.1 Window types

Window glazing types affect the amount of solar heat gains admitted indoors, particularly during sunny days. Windows that can reduce solar heat gain incorporate tinted glazing or spectrally selective coatings. In general, windows with a low value for the solar heat gain coefficient (SHGC < 0.4) fulfil this purpose, but there is an energy penalty in winter where solar heat gain to the indoors is desirable.

10.2 Solar shading devices

Solar shading devices for windows can significantly reduce solar heat gain from windows. Exterior shading devices are the most efficient in this respect, whereas the use of interior shading devices has a limited effect in reducing heat gain indoors.

10.3 Natural ventilation

Natural ventilations is driven by wind speed and/or stack effect, and is activated when the outdoor temperature is cooler than the indoor temperature. Natural ventilation therefore provides fresh outdoor air to the indoors and removes internal heat gains, resulting in cooler indoor temperatures. Natural ventilation can be accomplished by opening windows on different facades of building, or allowing air movement from bottom to top floors using the combined stack and wind effect. Cross ventilation, where outdoor air enters from one façade and exits from the opposite façade, is the most efficient means of natural ventilation. Wind and building height may also play a significant role to achieve this significant natural cooling effect.

10.4 Personal fan ventilation

Personal fan ventilation uses task, portable or ceiling fans to create air movement around a building occupant's body to remove body heat and thus creating a cooling effect. However, fan ventilation does affect the indoor temperature. Depending on the fan air speed at the occupant body level, a cooling effect of a few degrees Celsius can be achieved.

10.5 Mechanical ventilation

Mechanical ventilation uses dedicated fans to drive outdoor air indoors (supply ventilation or heat recovery ventilation) or drive out indoor air (exhaust ventilation) to achieve lower indoor temperatures, if the outdoor temperature is cooler than the indoor temperature. Mechanical ventilation can be operated continuously (e.g., heat recovery ventilation) or only during the nighttime where the outdoor temperature is usually lower than the indoor temperature. An adequate amount of air flow rate is needed to remove internal heat and create this cooling effect.

10.6 Mechanical cooling

Mechanical cooling using air conditioners is the most effective method to control indoor temperature. Mechanical cooling costs money for building owners or users, and is therefore the last resort to consider after passive cooling measures. Also this option is not available during a utility blackout.

10.7 Reflective building envelopes

Coatings placed on claddings of the building envelope, including roofs that reflect sunlight, can significantly reduce solar heat gain transmission through the envelope to indoor spaces, particularly on sunny days. However, the effectiveness of such measures will depend on the insulation levels behind the cladding or beneath the roof. The use of high insulation levels in envelopes reduces the effectiveness of this measure.

Single-Detached Homes

11 OVERHEATING IN SINGLE DETACHED HOMES

The overheating evaluation methodology presented in Sections 6 and 9 was applied to residential buildings under the current climate and future projections in Ottawa (Ontario). The building simulation procedure was used to obtain results of overheating in archetypical single detached homes built according to two construction types (light and medium mass) with four local construction practices: old (1980s), retrofitted according to the requirements of the current national building code (NBC) (NRC, 2015), current (or new) according to the NBC, and future net zero energy (NZE) (with 30% increase in insulation levels of building envelopes). The archetype home model (Figure 76 of Appendix A) consists of four thermal zones: un-occupied basement, first floor representing living room and kitchen spaces where occupants spend their time before going to sleep, second floor for bedrooms where occupants sleep, and attic space. Details on the simulation procedure and home characteristics are presented in Appendix A. The following sections presents the results of overheating for the selected mitigation measures as described in Section 10.

11.1 Effect of window types

Figure 21 shows the severity of overheating calculated under the current climate for various window types (Table 22) of single detached homes of light construction practice (i.e. old, retrofit, current, and NZE). The windows were covered by internal blinds, which were closed during summertime and open otherwise. According to the criteria of overheating given in Section 6, all homes overheated (severity > 230 °C·h). However, old and leaky homes had significantly lower risk of overheating, followed by retrofitted homes, new (current) homes, and future NZE homes. Windows that had a low value for Solar Heat Gain Coefficient (SHGC) resulted in a lower risk of overheating. Green tinted double glazed windows having low solar heat, low-e coatings (Dgreen+eL; SHGC = 0.30) was the best measure, that can reduce overheating risk by 57% compared to double clear high solar heat, low-e windows (Dclear+eH; SHGC = 0.67), followed by double clear low solar heat, low-e windows (Dclear+eL; SHGC = 0.42). Ironically, triple clear windows with high solar heat low-e (Tclear+eH; SHGC = 0.57) resulted in significantly higher risk of overheating, particularly in NZE homes.

Window effects

Windows with low SHGC values (< 0.42) are effective, but will need additional measures to minimize overheating risk in homes with limited natural ventilation (windows remain mostly closed in summer).

Figure 22 shows the effect of window type covered by internal blinds on the living room (first floor) temperature during the summer heat wave period in 2010 for a home of current light construction practice. Windows with low SHGC values (such as Dgreen+eL and Dclear+eL) may reduce the indoor temperatures by up to 4.5°C. Windows with high SHGC values (such as Dclear+eH, Tclear+eH) resulted in the highest peak indoor temperatures (46.5°C).

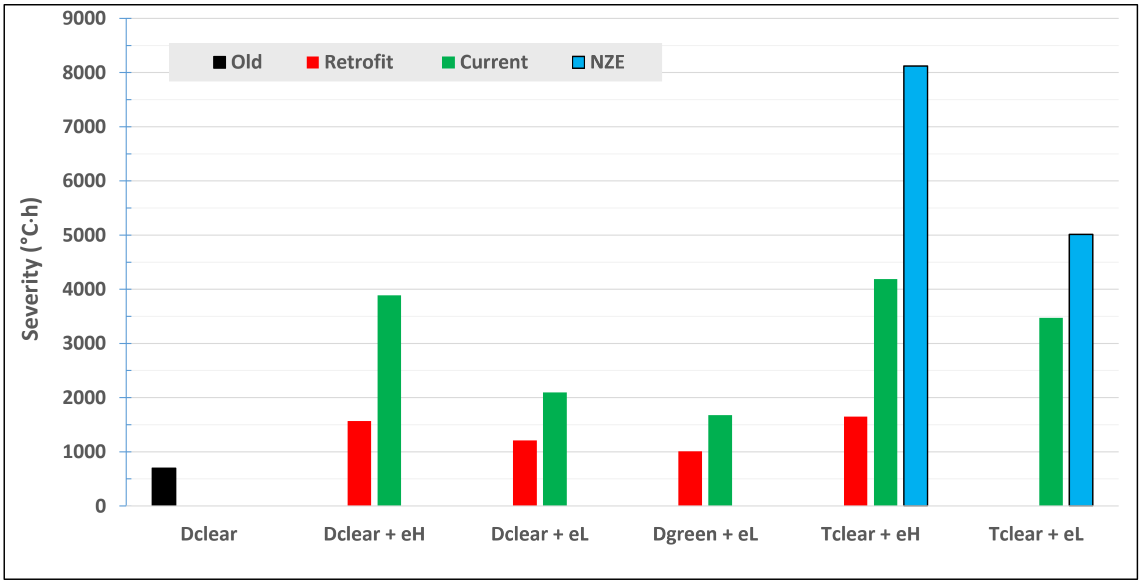


Figure 21: Effect of window types covered by internal blinds on overheating severity for single-detached houses with four light constructions practices (old, retrofit, current, and NZE)

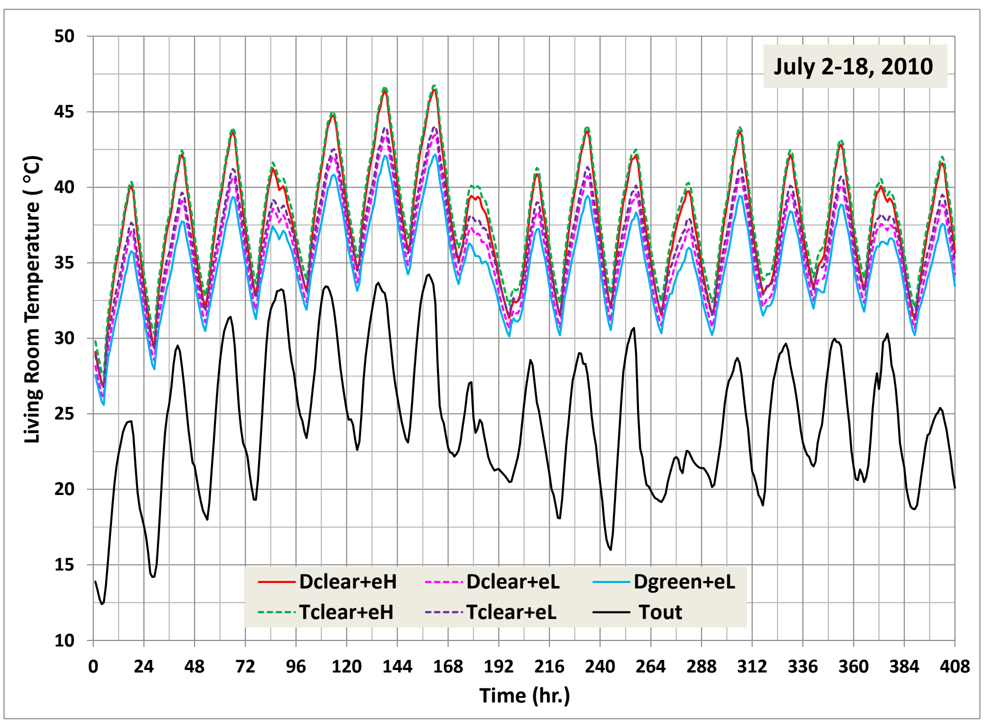


Figure 22: Effect of window types covered by internal blinds on the living room temperature during the summer heat wave period in 2010 for single-detached houses with the current light construction practice

Figure 23 shows the effect of window types covered by internal blinds on the annual energy use for heating and cooling of homes. In contrast to overheating, the tinted windows (Dgreen+eL) resulted in the highest heating energy use (about 11% higher than double clear high solar heat low-e windows, Dclear+eH). Triple clear glazing with high solar heat, low-e coatings (Tclear+eH) had the lowest energy use for heating (about 8% compared to Dclear+eH).

Windows are usually selected to minimize the annual energy use or energy cost of homes, but this selection would increase the risk of overheating, particularly in homes with limited use of natural ventilation (windows remain mostly closed in summer for whatever reasons such as privacy, exterior noise, security, etc.). Whereas the health and safety of building occupants is paramount, retrofitting or designing new homes should follow a trade-off to minimize both home energy use and overheating risk, by implementing effective passive or active measures such as whole house ventilation; this is discussed later on in the document.

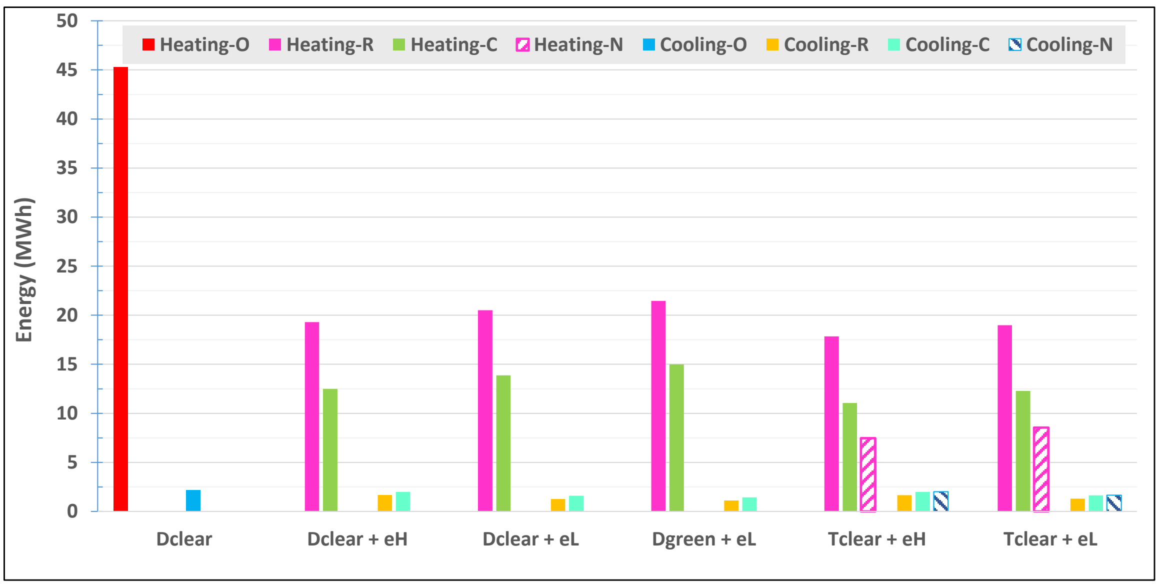


Figure 23: Effect of window types covered by internal blinds on annual energy use for heating and cooling of single-detached houses with four light constructions practices (old, retrofit, current, and NZE)

11.2 Effect of solar shading devices

Figure 24 shows the severity of overheating calculated under the current climate for various types of shading devices (Table 21) for single detached homes having typical windows and of light construction practice (i.e. old, retrofitted, current and NZE). The shading devices are assumed closed during the summertime and open otherwise. Exterior shadings are the most effective shading device, followed by electrochromic windows, thermochromic windows, and reflective interior blinds. Compared to internal blinds, exterior shadings may reduce the risk of overheating by more than 90%, followed by 25 to 71% for electrochromic windows, 22 to 70% for thermochromic windows, and 11 to 30% for internal reflective blinds. In retrofitted homes, exterior shading can minimize or eliminate overheating risk according to the overheating criteria given in Section 6. Due to their higher air leakage rates, retrofitted homes present a lower risk of overheating than new or future NZE homes. In new (current) or future NZE homes, exterior shadings should be combined with other measures, such as whole house ventilation, to minimize or eliminate the risk of overheating.

Shading effects

Exterior shadings are effective to minimize overheating risk in retrofitted homes. In new or NZE homes, exterior shadings should be combined with other measures such as whole home ventilation to minimize overheating risk.

Figure 25 shows the effect of shading devices on the living room temperature during the summer heat wave period in 2010 for homes with typical windows following current light construction practice. Exterior shadings may significantly reduce the peak indoor temperatures by up to 9°C compared to internal blinds, followed by 3°C for dynamic windows (electro or thermo-chromic).

Figure 26 shows the effect of shading devices on annual energy use for heating and cooling of homes with typical windows. Conventional (interior and exterior) shading devices primarily reduce the cooling energy use in summer but have non-significant effects on heating energy use in winter. However, dynamic windows may increase the heating energy use by up to 40% compared to internal blinds due to their lower SHGC (< 0.41), particularly in NZE homes.

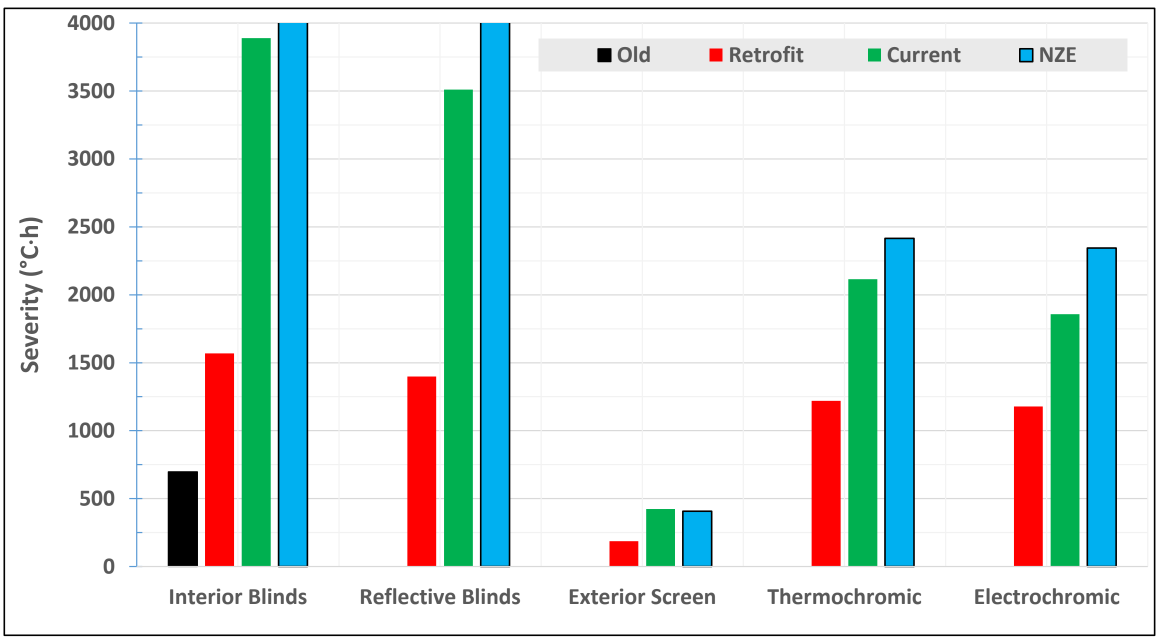


Figure 24: Effect of shading devices on overheating severity for single-detached homes with typical windows and four light constructions practices (old with Dclear, retrofit with Dclear+eH, current with Dclear+eH, and NZE with Tclear+eH)

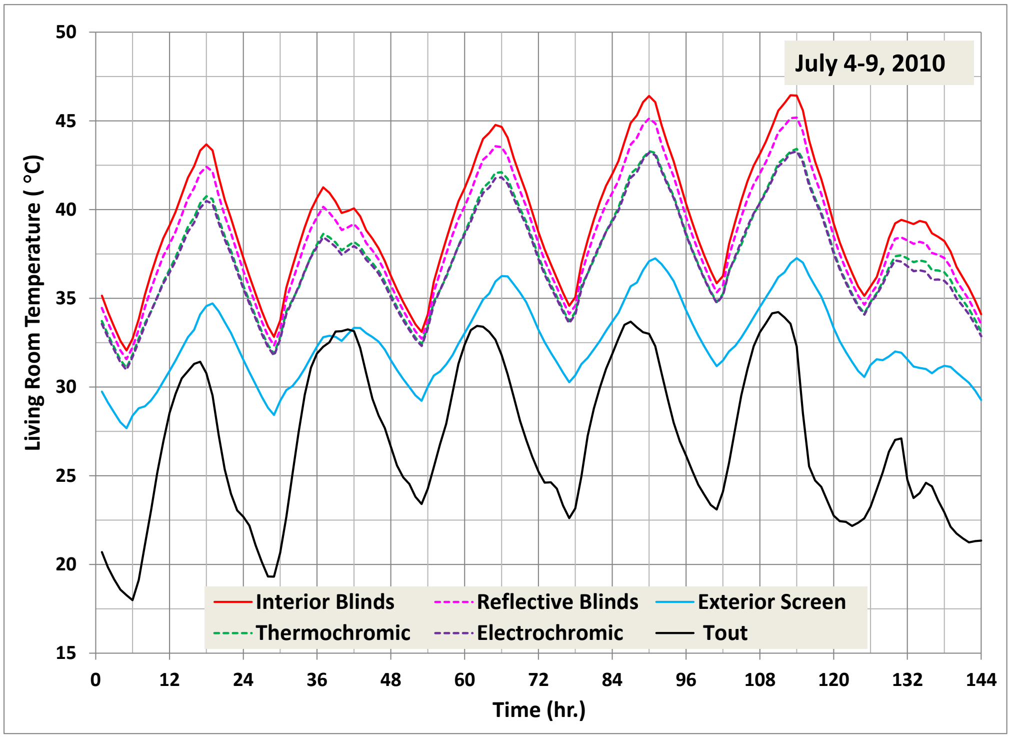


Figure 25: Effect of shading devices on the living room temperature during the summer heat wave period in 2010 for single-detached homes with typical windows (Dclear+eH) and the current light construction practice

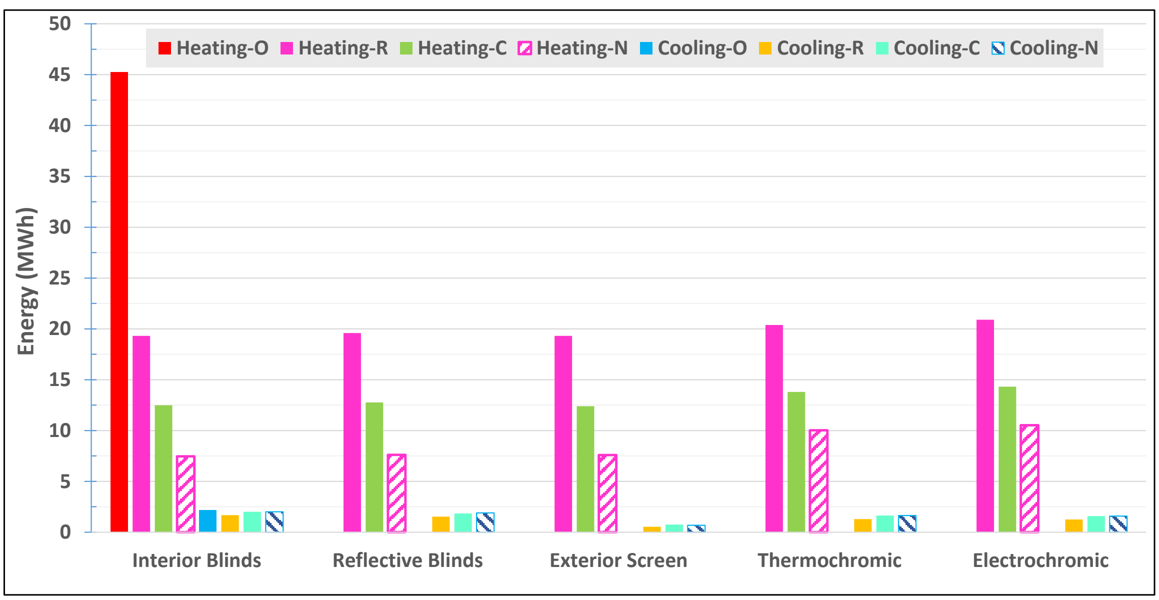


Figure 26: Effect of shading devices on the annual energy use for heating and cooling for single-detached homes with typical windows and four light constructions practices (old with Dclear, retrofit with Dclear+eH, current with Dclear+eH, and NZE with Tclear+eH)

11.3 Effect of house ventilation

Four ventilation strategies were assessed for overheating, including: (1) Natural ventilation by opening 25% of the home window surface areas when the indoor temperature of each thermal zone exceeded 26°C and the outdoor temperature. (2) Nighttime ventilation by operating the home exhaust fans (kitchen and bathrooms) and increasing their airflow rates to 10 times their nominal airflow rate (i.e., 220 litre/s or 466 CFM) from 10:00 PM to 9:00 AM; (3) mixed mode, natural ventilation + nighttime ventilation; and (4) personal (ceiling or portable) fan ventilation combined with natural ventilation. To calculate and balance the air flow rates in the different thermal zones within the home, natural and exhaust fan ventilation were integrated with the air flow network of the entire home.

Figure 27 shows the effect of ventilation strategies on the severity of overheating for homes having typical windows and following light construction practices (i.e. old, retrofit, current, and NZE). Natural ventilation was effective in minimizing or eliminating overheating risk in the four types of homes. Nighttime ventilation was as well effective but did not eliminate the overheating risk. Nighttime ventilation could reduce overheating risk from 47% (retrofit) to 83% (NZE) compared with no ventilation. Mixed mode ventilation did not, however, produce any additional significant effect on top of natural ventilation.

Whole house ventilation

Passive natural ventilation by opening windows in summer is an effective strategy to minimize the risk of overheating in all types of homes. Nighttime ventilation is as well effective, but will need to be combined with other measures to minimize overheating risk.

Figure 28 shows the effect of house ventilation strategies on the living room temperature during the summer heat wave period in 2010 for homes with typical windows and following current light construction practice. Natural ventilation may reduce the daytime peak indoor temperatures by up to 11.5°C compared to no ventilation, followed by 2°C for nighttime ventilation.

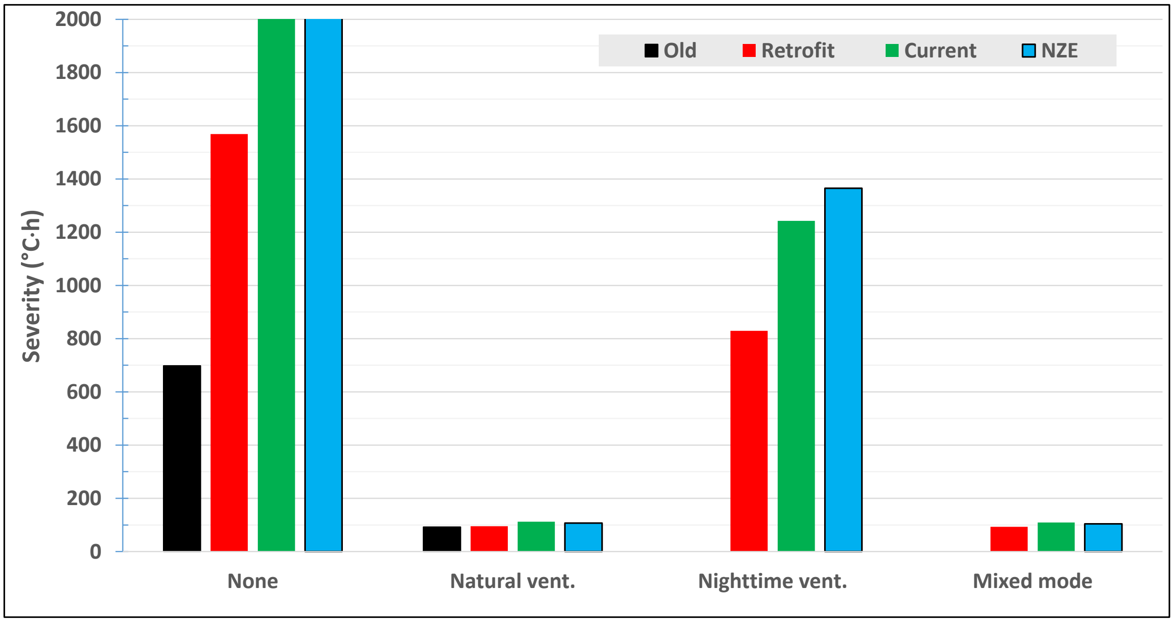


Figure 27: Effect of whole house ventilation on overheating severity for single-detached houses with typical windows and four light constructions practices (old with Dclear, retrofit with Dclear+eH, current with Dclear+eH, and NZE with Tclear+eH)

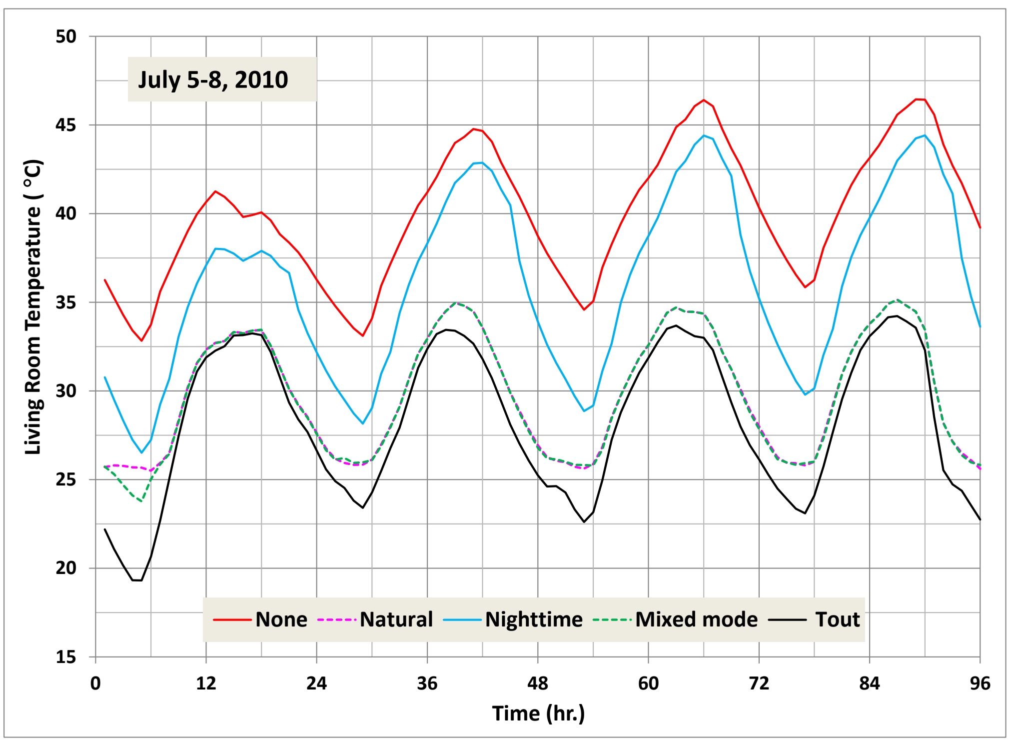


Figure 28: Effect of whole house ventilation strategies on overheating severity for single-detached houses with typical windows (Dclear+eH) and the current light constructions practice

Figure 29 shows the effect of personal (ceiling or portable) fan ventilation (operated according to the space occupancy schedule) on overheating severity in homes having typical windows and following current light construction practice. Personal fans induced air movement around the body of occupants, thus creating a cooling effect, but they did not affect indoor temperatures. Fan air speed may reduce overheating risk by 37 to 54%, depending on the air speed in proximity to an occupant's body. Fan air speeds close to 2 m/s resulted in the same overheating level as nighttime space ventilation using exhaust fans (operated from 10:00 PM to 9:00 AM). To minimize or eliminate overheating risk, the fan ventilation strategy should be combined with other measures. One of the measures commonly used in free running buildings is natural ventilation, such as by opening windows, as mentioned before. However, for natural ventilation to be effective, cross air flows in the home spaces should be created in which outdoor air is driven in from one façade and then exits from the opposite facade. To illustrate this effect, Figure 30 shows the effect of various combinations of façade window openings such as: opening all houses windows by 25% (NESW, cross ventilation), opening windows of the south and north façades (SN, cross ventilation), opening windows of the west and east facades (WE, cross ventilation), opening windows of the south and west façades of the first floor and those at the north and east façades of the second floor (SW1NE2, vertical stack effect and cross ventilation), opening windows of the south and west facades (SW, two-sided ventilation), opening windows of the north and west facades (NW, two-sided ventilation), and only opening windows of the south façade (S, single-sided ventilation). All ventilation cases were effective in minimizing or eliminating the risk of overheating, except the single-sided ventilation strategy (S). Combining the single-sided natural ventilation with personal fan ventilation (S+F-0.8) can be more effective than cross ventilation alone in minimizing or eliminating overheating risk in homes.

Fan ventilation

Fan ventilation can be an alternative measure to nighttime ventilation. Combination of fan ventilation and natural ventilation (opening windows of at least one façade) is effective to minimize the risk of overheating in old or highly insulated houses.

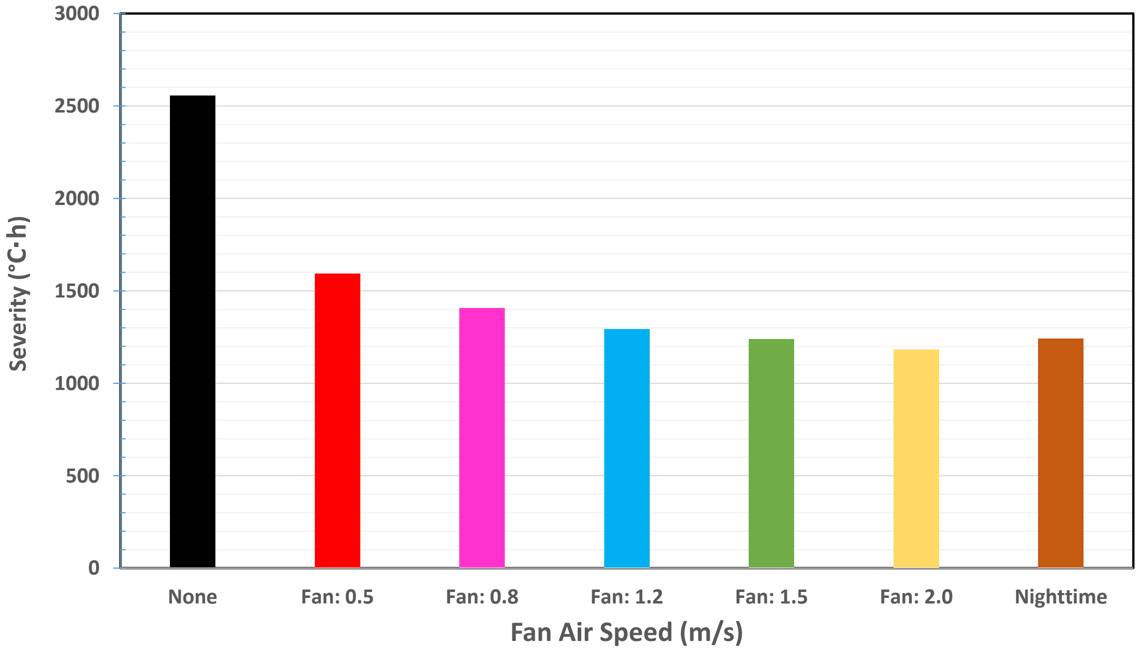


Figure 29: Effect of personal fan ventilation on overheating severity for single-detached houses with typical windows and the current light constructions practice

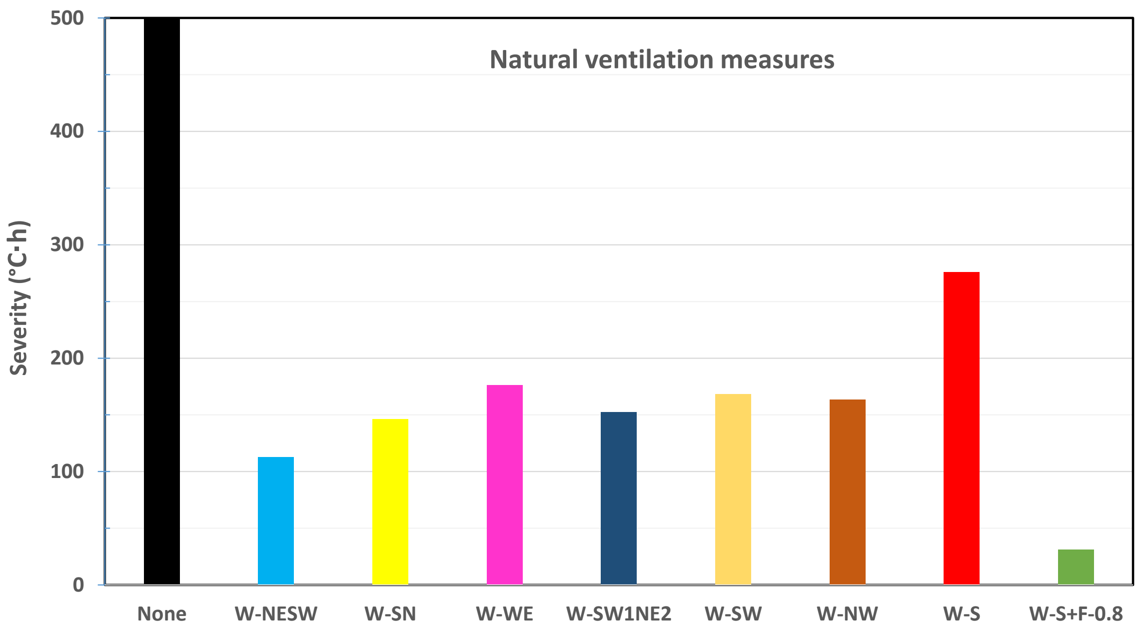


Figure 30: Effect of window opening strategy on overheating severity for single-detached houses with typical windows and the current light constructions practice

11.4 Effect of mechanical cooling with relaxed setpoint

Operating a central cooling system or window air conditioner during extreme heat events in summer with a relaxed (higher) set point temperature is sometimes required to reduce the prohibitive cost of cooling. Furthermore, this strategy would also benefit the electric utilities in reducing the electric demand during peak hours. Figure 31 shows how this strategy affects overheating risk in homes of four different local construction practices. Relaxing the cooling setpoint temperature to 31°C (corresponding to SET = 30°C, slightly warm sensation) can effectively reduce overheating risk during extreme heat events, or eliminate it in old houses (severity < 230°C*h). However, eliminating overheating risk in highly insulated homes may need combining this strategy with other passive strategies such as opening windows during nighttime or the use of nighttime mechanical ventilation to purge the home from excessive internal heat gains accumulated during daytime.

Mechanical cooling

Mechanical cooling with relaxed setpoint (31°C) is effective to eliminate the risk of overheating in old houses, but will need additional passive measures such as nighttime ventilation to minimize overheating risk in highly insulated houses.

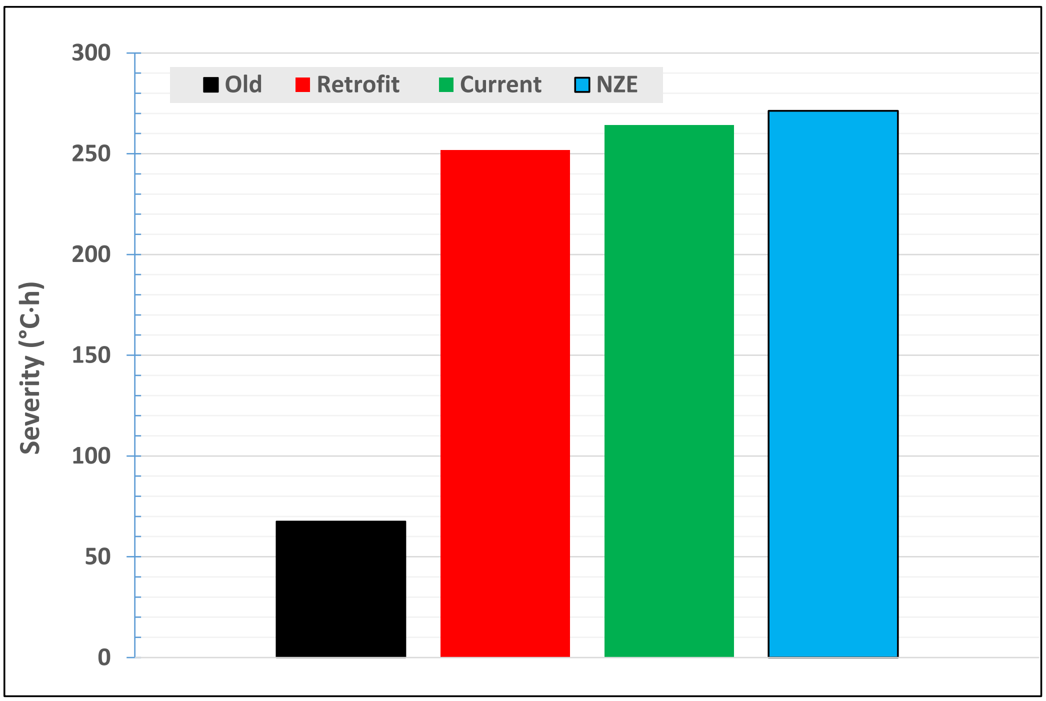


Figure 31: Effects of mechanical cooling with relaxed setpoint on overheating severity for single-detached houses with typical windows covered by internal blinds and four light constructions practices (old, retrofit, current, and NZE)

11.5 Effect of building construction types

Two types of house construction were assessed for overheating (Table 23): (1) light construction, with vinyl claddings; and (2) medium construction, with brick veneer cladding.

Figure 32 shows the effect of construction type on the severity of overheating in homes having typical windows covered by internal blinds and four local construction practices (i.e. old, retrofit, current, and NZE). In those homes, windows were assumed open to enable passive natural ventilation. The two construction types had negligible effects on overheating risk. This might be due to the fact that the high level of insulation behind the medium mass cladding prevents heat stored in the cladding to reach the interior space.

Construction types

House construction types (light or medium mass) have no significant effect on overheating risk.

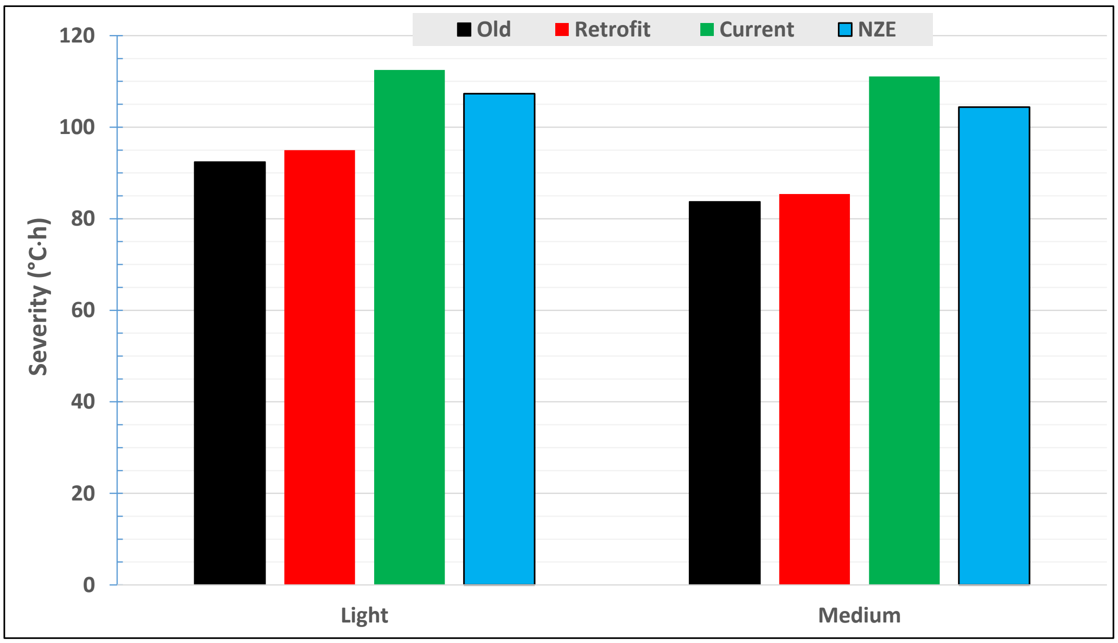


Figure 32: Effects of construction types on overheating severity for single-detached houses with open typical windows covered by internal blinds and four local constructions practices (old, retrofit, current, and NZE)

11.6 House energy use and overheating risk

The relationship between total energy use (electric and gas) and overheating risk in homes is very important for thermal resilience designs of buildings to maintain healthy and safe environments. Requirements for building to have high energy efficiency has been rising in past decades to contravene the ever-increasing effect of greenhouse gas emission on the climate; little, however, has been known for the associated risk to overheating.

Figure 33 shows how the home total (electric and gas) energy use is related to overheating severity. The data are plotted for all types of home constructions and windows. Windows were assumed closed (no natural ventilation) and covered by internal shading devices (including dynamic windows, but exterior shadings were excluded). It is clear that the total energy use is inversely proportional to overheating risk in airtight or naturally unventilated homes. The higher the energy efficiency requirement (or lower energy use), the higher the overheating risk. It is therefore recommended that passive or active measures be implemented to reduce overheating risk in new or future NZE homes if mechanical cooling is not an option. Those measures may include exterior shades with or without personal fan ventilation, natural ventilation (if windows are allowed to be opened in summer), mechanical ventilation using supply or exhaust fans, heat recovery ventilators but with higher flow rates than nominal values with a summertime bypass option to avoid pre-heating of the outdoor air.

Energy use & overheating

Overheating risk is inversely proportional to total energy use in airtight or naturally unventilated homes. Highly insulated homes should therefore implement passive or active measures to reduce overheating risk.

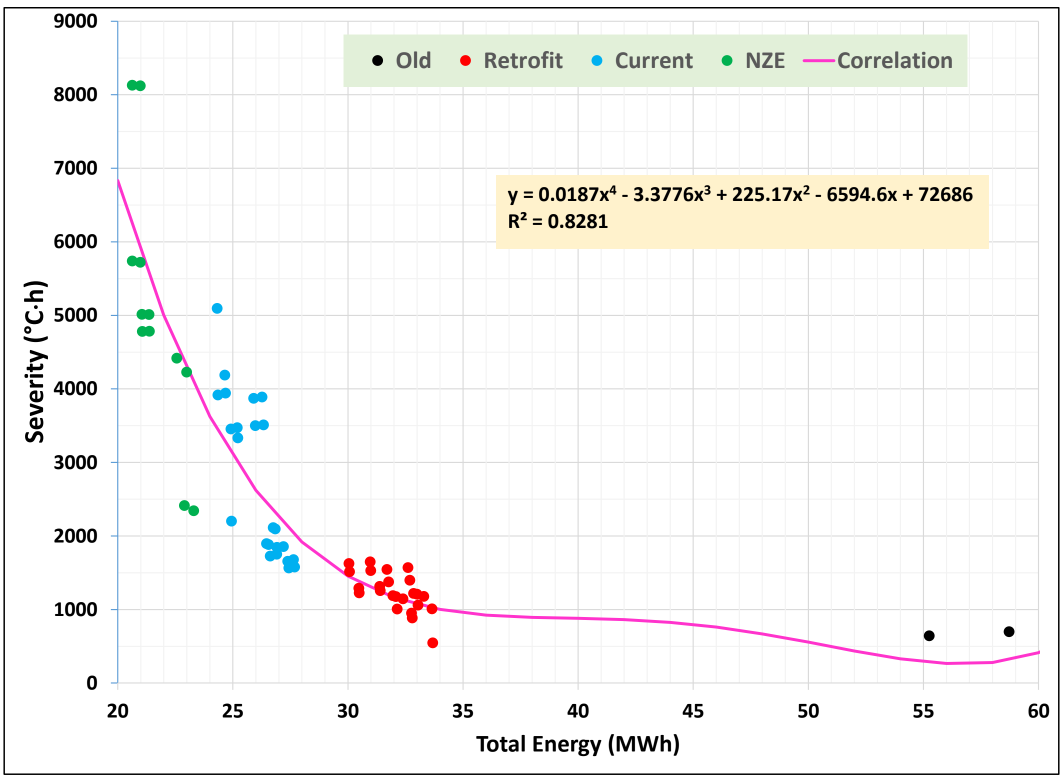


Figure 33: Relationship between total (electric and gas) energy use and overheating risk in naturally unventilated single-detached houses with four local constructions practices (old, retrofit, current, and NZE)

11.7 Effect of global warming on overheating risk and energy

Simulations were conducted for seven global warming scenarios representing global temperature changes of 0.5°C to 3.5°C. These include: GW0.0 (current climate), GW0.5 (2001-2031), GW1.0 (2013-2043), GW1.5 (2024-2054), GW2.0 (2034–2064), GW2.5 (2044-2074), GW3.0 (2053-2083), and GW3.5 (2062–2092). Figure 34 to Figure 36 show the effect of global warming on the severity and intensity of overheating events in retrofitted, new (current) and NZE homes, respectively, with natural ventilation enabled (open windows) or not enabled (closed windows). All windows were equipped with typical internal blinds, which were assumed closed during summertime. The severity and intensity of overheating events increase with the global warming degree. By the end of the 21st century, the severity and intensity of overheating in retrofitted homes will increase from 219% (no natural ventilation) to 1252% (with natural ventilation), and from 40% (no natural ventilation) to 422% (with natural ventilation), respectively, compared to the current climate (GW0.0). The evident sharp increase in overheating severity in naturally ventilated homes is due to the fact that overheating events in such homes are shorter than in homes without natural ventilation. Natural ventilation can be an effective measure to eliminate overheating risk up to GW1.0 (2013-2043). Similarly, for new or NZE homes, the severity and intensity of overheating increase from 100% (no natural ventilation) to 1165% (with natural ventilation), and from 14% (no natural ventilation) to 282% (with natural ventilation), respectively. By the end of the global warming scenario GW1.0, natural ventilation in such homes is still effective but would need to be combined with other measures to minimize or eliminate overheating risk (severity < 230°C·h).

Global warming

GW increases the severity and intensity of overheating events by up to 1252% and 422%, respectively, in naturally ventilated homes. By the end of GW1.0, new or NZE homes would need additional measures to combine with natural ventilation to minimize the risk of overheating. Furthermore, GW may reduce heating energy by up to 31% and increase cooling energy by up to 35% in new or NZE homes.

In Figure 37 the effect of global warming is shown on the relative changes (with respect to GW0.0) in heating, cooling, and total (heating + cooling) energy use of retrofitted, new (current) and NZE homes. Global warming decreased the heating energy use but increased the cooling energy use. By the end of the 21st century, the changes in the energy usage of retrofitted homes was - 30% for heating and 43% for cooling. For new (or NZE) homes, the changes in the energy usage was - 29% (-31%) for heating and 35% (32%) for cooling.

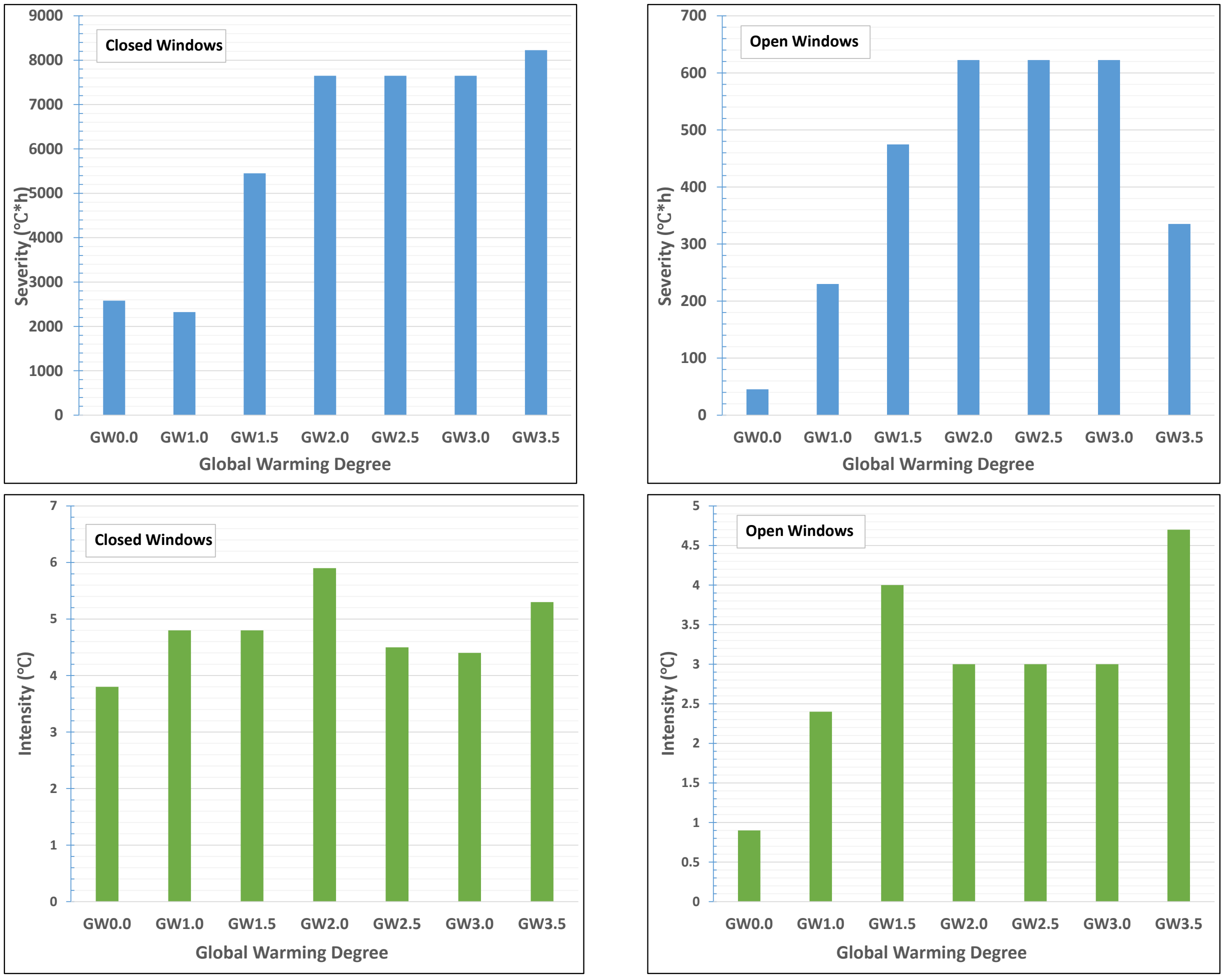


Figure 34: Effects of global warming scenarios on severity and intensity of overheating in single-detached retrofitted homes with typical windows covered by internal blinds and natural ventilation enabled (open windows) or not enabled (closed windows).

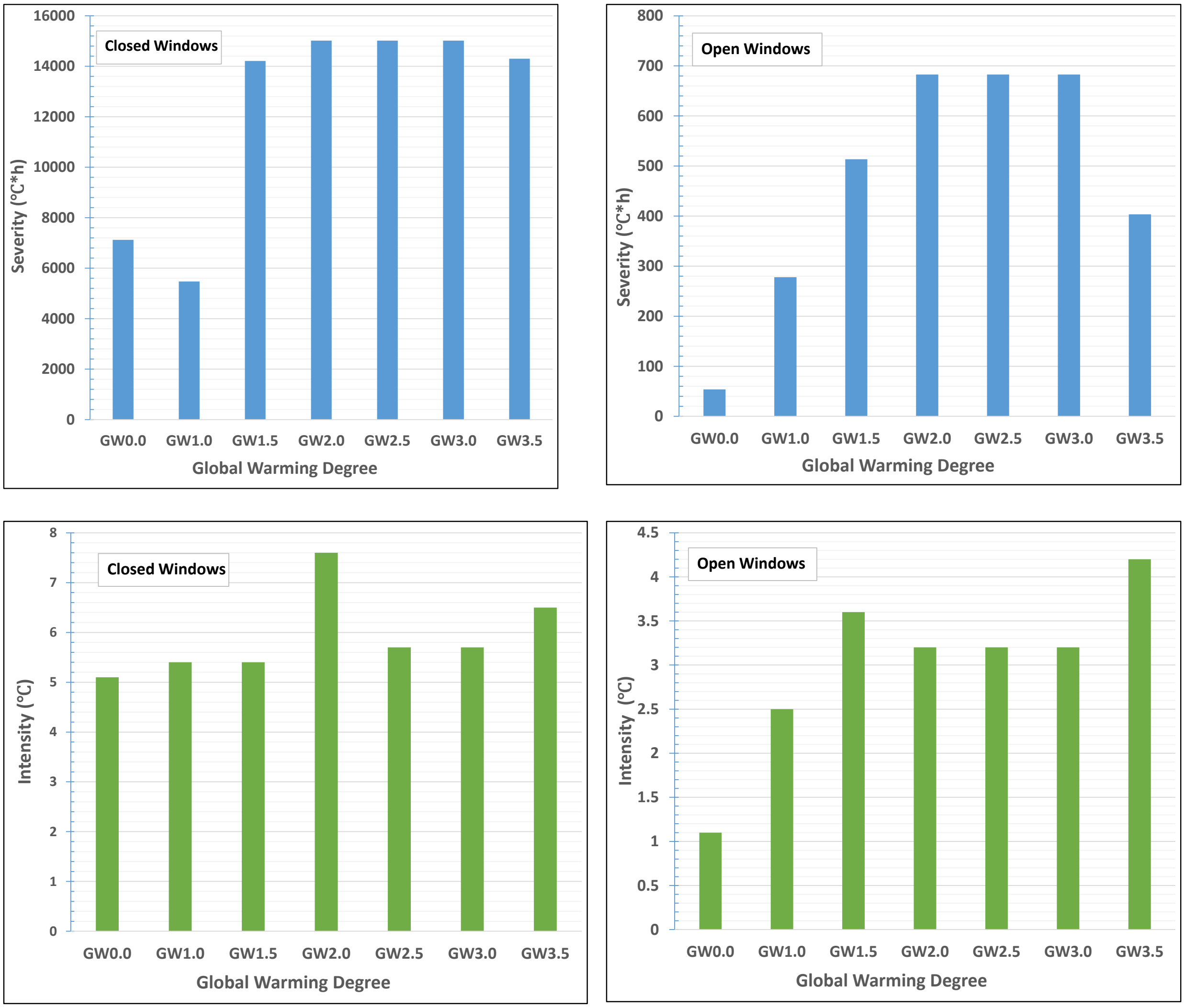


Figure 35: Effects of global warming scenarios on severity and intensity of overheating in new single-detached homes with typical windows covered by internal blinds and natural ventilation enabled (open windows) or not enabled (closed windows).

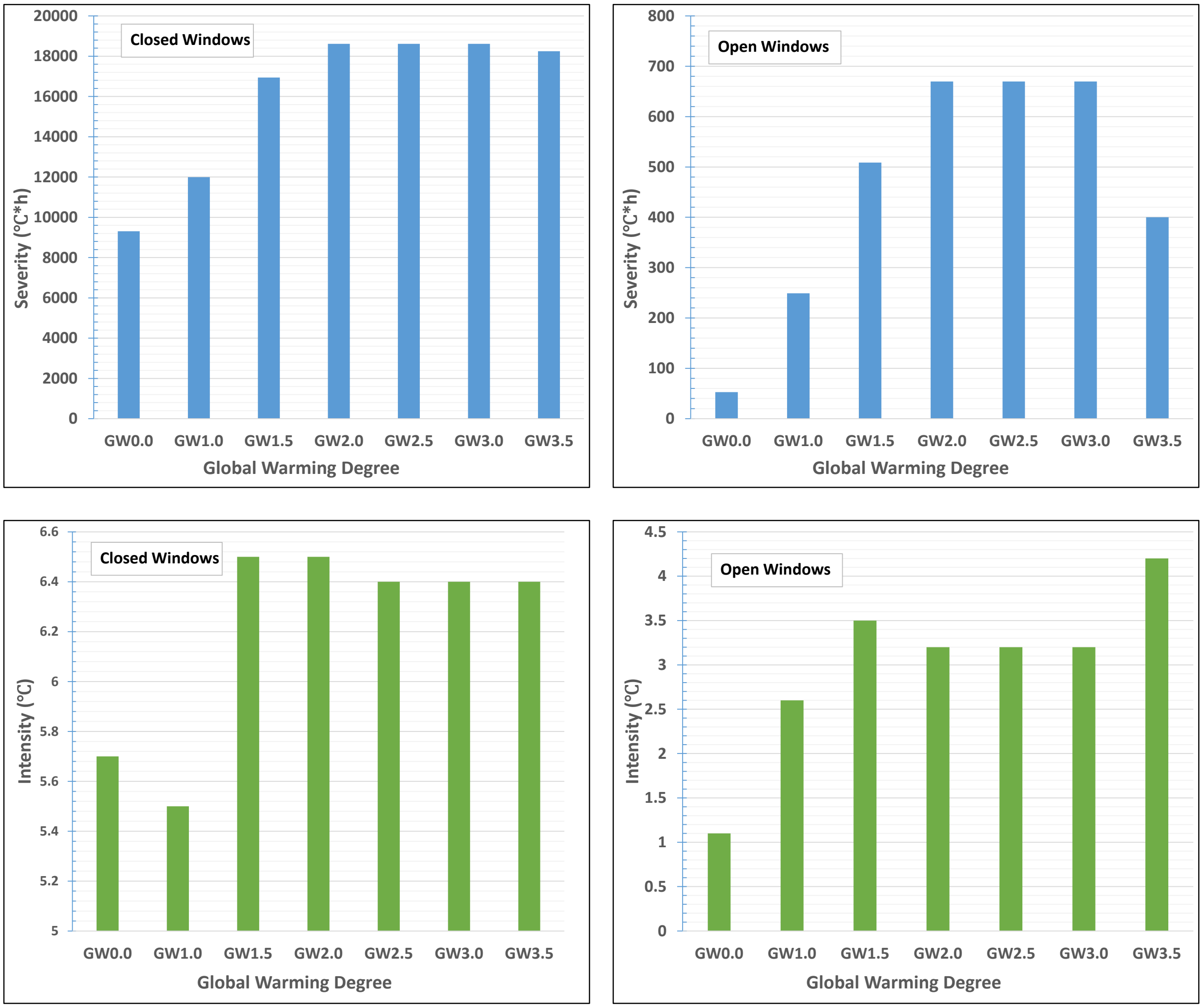


Figure 36: Effects of global warming scenarios on severity and intensity of overheating in NZE single-detached homes with typical windows covered by internal blinds and natural ventilation enabled (open windows) or not enabled (closed windows).

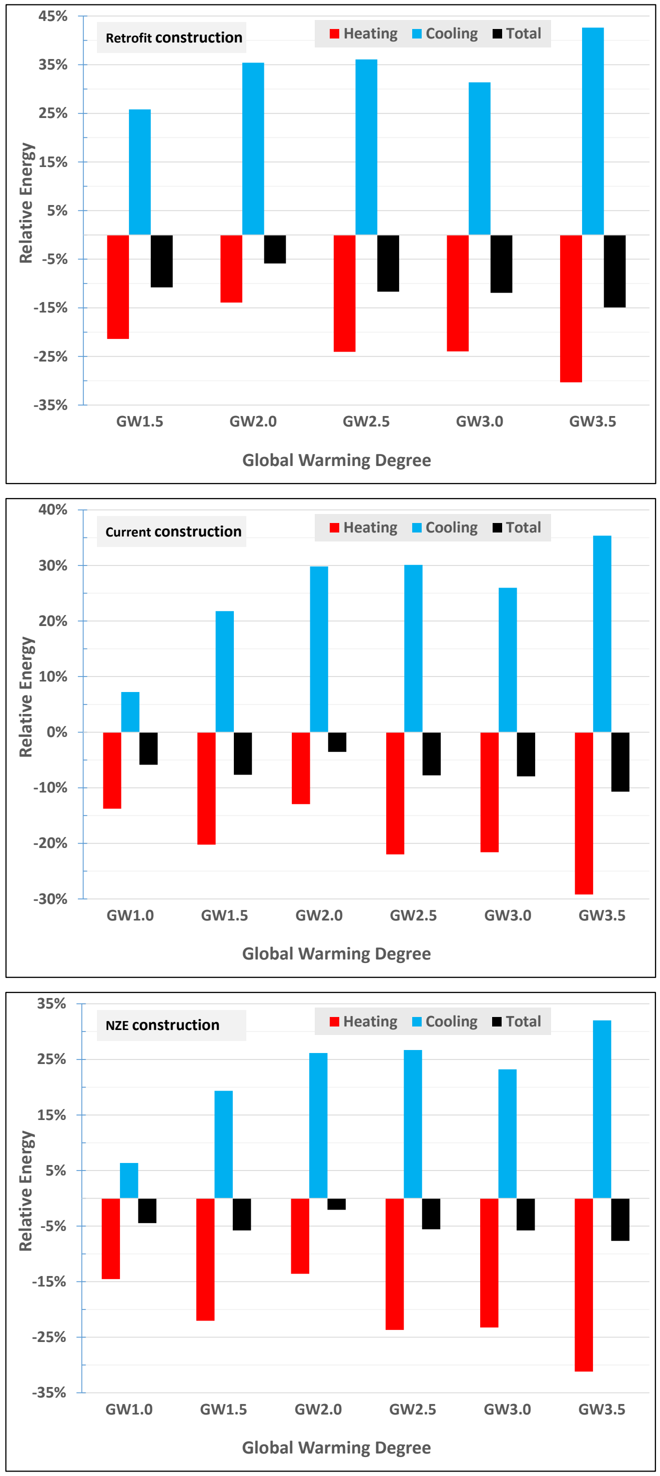


Figure 37: Effects of global warming scenarios on relative energy changes for heating, cooling and total energy of single-detached homes with typical windows covered by internal blinds

Row-Houses

Courtesy of: http://skyscraperpage.com

12 OVERHEATING IN ROW HOUSES

The same methodology applied to single detached homes (Section 11) is again applied to row houses. A row house shares two party walls with the adjacent homes and has two exterior walls (Figure 77 in Appendix A). The exterior walls were assumed facing the north and south directions. More details on the home characteristics are presented in Appendix A. The following sections presents the results of overheating in such homes for the selected measures as described in Section 10.

12.1 Effect of window types

Figure 38 shows the severity of overheating calculated under the current climate for various window types (Table 22) of row houses for different light construction practices (i.e. old, retrofit, current, and NZE). The windows were assumed closed and covered by internal blinds. Row houses present a significantly lower risk of overheating than single detached houses (Figure 21). The severity of overheating in row houses can be reduced by 54 to 78% compared to single-detached homes. Overheating risk in old and leaky row houses is slightly under the threshold value of 230° C*h. In retrofitted homes, green tinted low-e windows (Dgreen+eL) can minimize or eliminate overheating risk according to the aforementioned criterion of Section 6. Other window types may need to be combined with other measures to minimize overheating risk. Green tinted low-e windows (Dgreen+eL; SHGC = 0.30) in new homes produce the lowest overheating risk, about 30% compared to double clear high solar heat low-e windows (Dclear+eH; SHGC = 0.67), followed by 20% for double clear low solar heat low-e windows (Dclear+eL; SHGC = 0.42). In new or NZE homes, windows with low SHGC values (< 0.42) need to be combined with other measures to minimize overheating risk. Ironically, triple clear windows with high solar heat low-e (Tclear+eH; SHGC = 0.57) result in significantly higher risk of overheating, particularly in NZE homes.

Figure 39 shows how the window type affects the indoor temperatures of living rooms (first floor) during the summer heat wave period in 2010 for a row house with the current light construction practice. Daytime peak indoor temperatures in row houses are 7°C lower than in single detached homes (Figure 22). Windows with low SHGC values (such as Dgreen+eL and Dclear+eL) may reduce the indoor temperatures by up to 2°C. Windows with high SHGC values (Dclear+eH, Tclear+eH) result in the highest daytime peak indoor temperatures (40°C).

Figure 40 shows the effect of window types covered by internal blinds on annual energy use for heating and cooling of row houses. Compared to single detached houses (Figure 23), the effect of window types on heating energy use is not significant (within 5% difference) due to lower window surface areas. It is therefore recommended to select window types that minimize overheating risk irrespective of energy use in such homes. In this regard, windows with low SHGC (< 0.42) should be considered, but will need to be combined with other passive measures such as personal fan ventilation, whole house ventilation, or other measures to minimize or eliminate overheating risk.

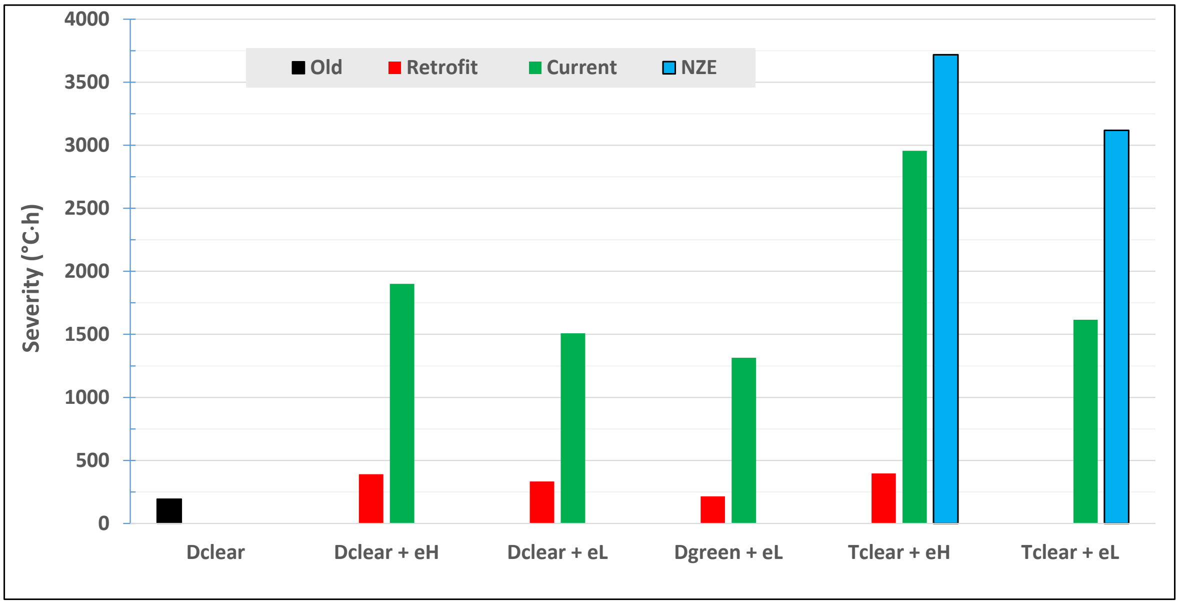


Figure 38: Effect of window types covered by internal blinds on overheating severity for row houses for light construction practice (old, retrofit, current, and NZE)

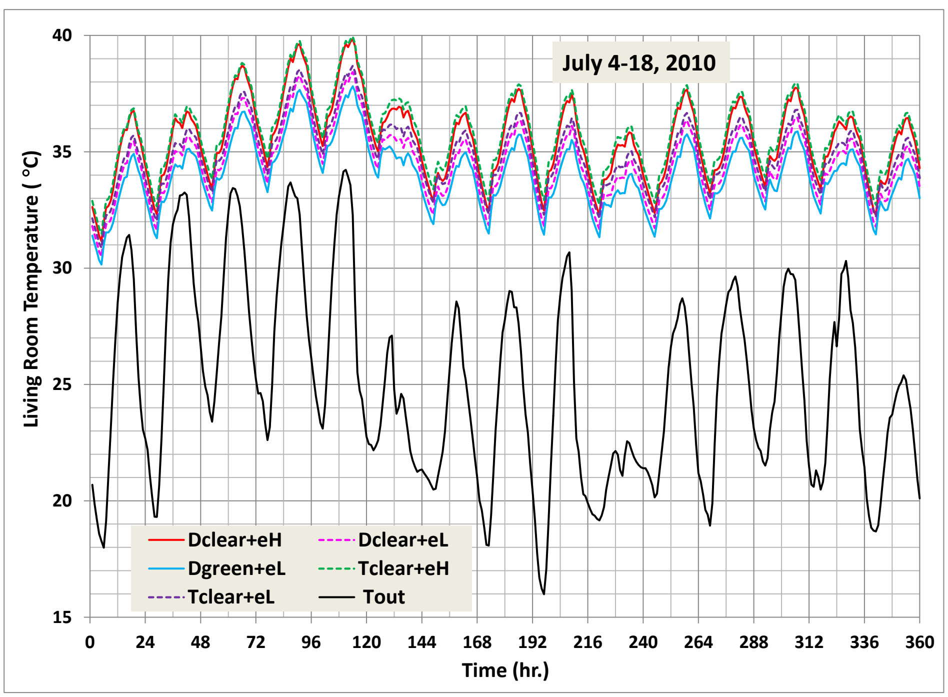


Figure 39: Effect of window types covered by internal blinds on the living room temperature during the summer heat wave period in 2010 for row houses with light construction practice

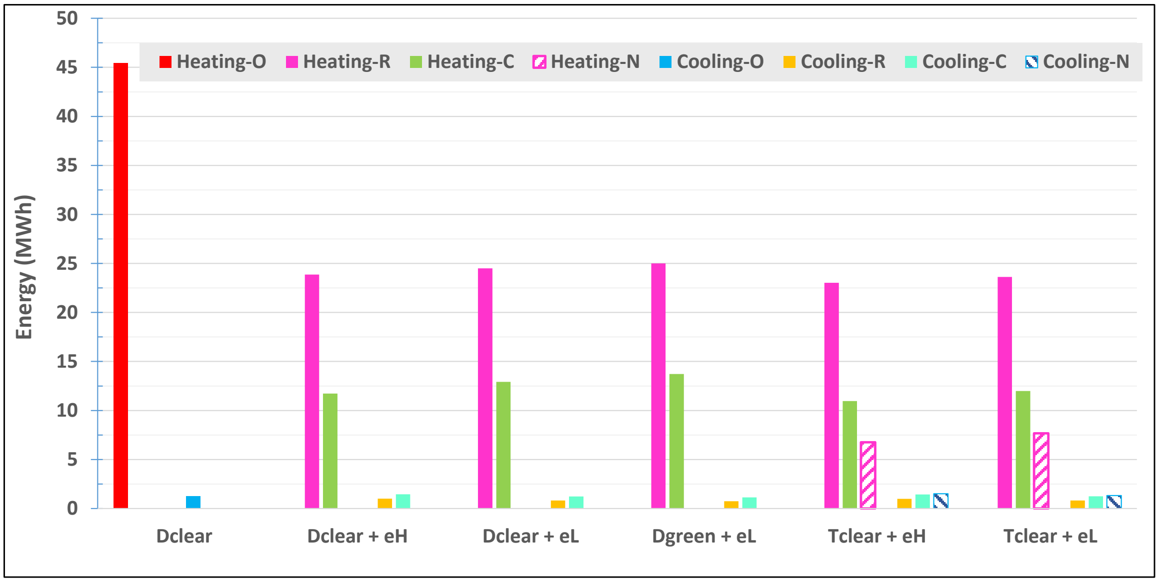


Figure 40: Effect of window types covered by internal blinds on annual energy use for heating and cooling for row houses for light construction practice (old, retrofit, current, and NZE)

12.2 Effect of solar shading devices

Shading effects

Exterior shadings and dynamic windows are effective to minimize overheating risk in retrofitted houses. In new or NZE houses, exterior shadings or dynamic windows will need to be combined with other measures such as whole house ventilation to minimize or eliminate the risk of overheating.

Figure 41 shows the severity of overheating calculated under the current climate for various types of shading devices (Table 21) for row houses with typical windows and different light construction practices (i.e. old, retrofitted, current and NZE). The shading devices were assumed closed during the summertime and open otherwise. Exterior shading devices are the most effective devices for all types of homes, followed by dynamic (electro or thermo-chromic) windows, and reflective internal blinds. Compared to internal blinds in new or NZE homes, exterior shading devices may reduce the risk of overheating by more than 80%, followed by 40% for dynamic windows, and 14% for internal reflective blinds. In retrofitted homes, exterior shadings and dynamic windows may minimize or eliminate the risk of overheating according to the criterion of Section 6 (severity < 230°C*h). In new or NZE homes, exterior shading devices and dynamic windows need to be combined with other relevant measures such as whole house ventilation or personal fan ventilation to minimize or eliminate overheating risk.

Figure 42 shows the effect of shading devices on the living room temperature during the summer heat wave period in 2010 for a row house having typical windows (Dclear+eH) and the current light construction practice. Exterior shading devices may significantly reduce the daytime peak indoor temperatures by up to 5°C compared to the use of internal blinds, followed by 2°C for electro or thermo-chromic windows.

Figure 43 shows the effect of shading devices on annual energy use for heating and cooling of row houses. Conventional (interior and exterior) shading devices primarily reduce the cooling energy use in summer but have non-significant effects on heating energy use in winter. However, dynamic (electro or thermo-chromic) windows may increase the heating energy use by up to 32% compared to internal blinds due to their lower SHGC (< 0.41), particularly in NZE homes

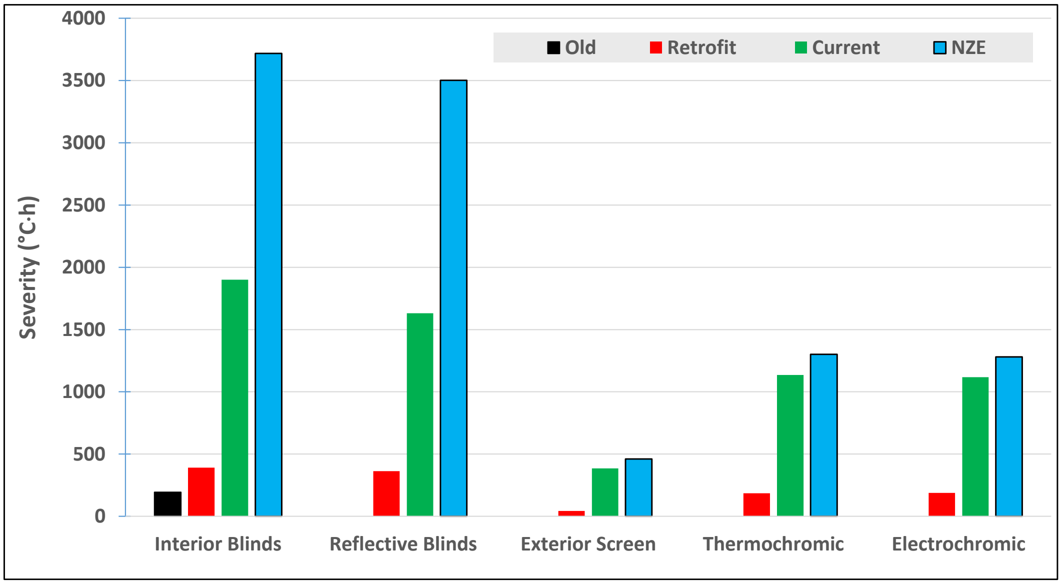


Figure 41: Effect of shading devices on overheating severity for row houses with typical windows and for light construction practice (Old: Dclear; retrofit: Dclear+eH; Current: Dclear+eH: and NZE: Tclear+eH)

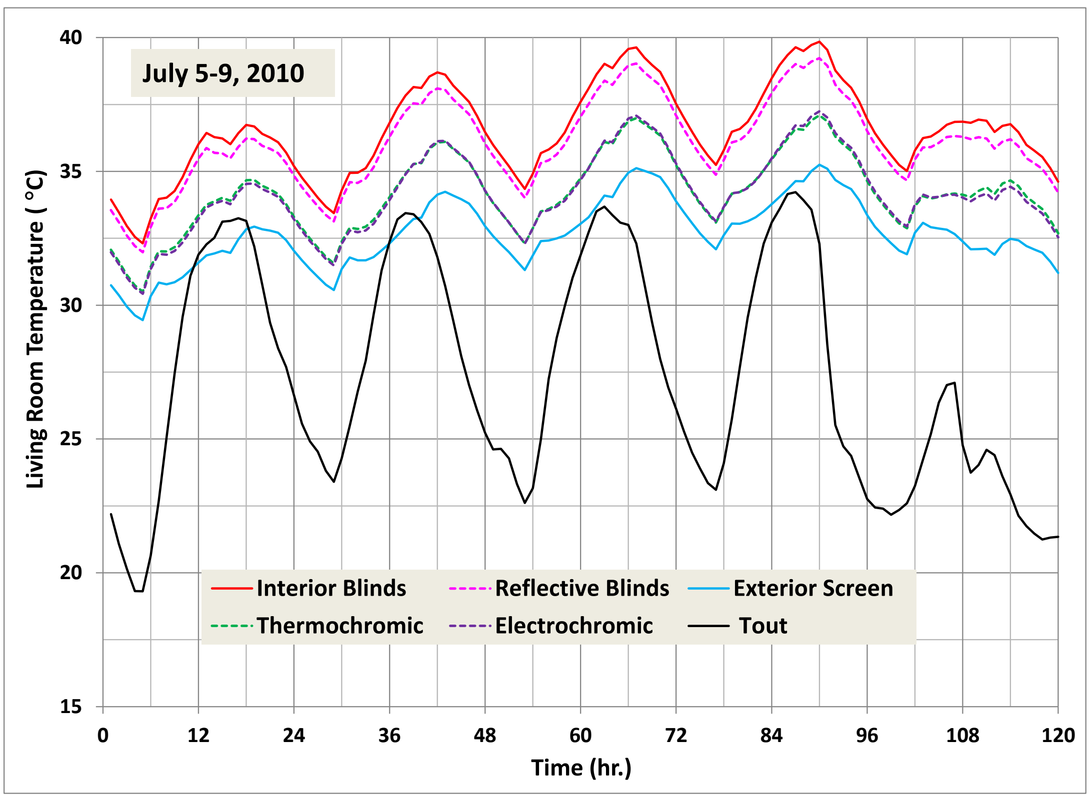


Figure 42: Effect of shading devices on living room temperature during summer heat wave period in 2010 of row houses with typical windows and current light construction practice

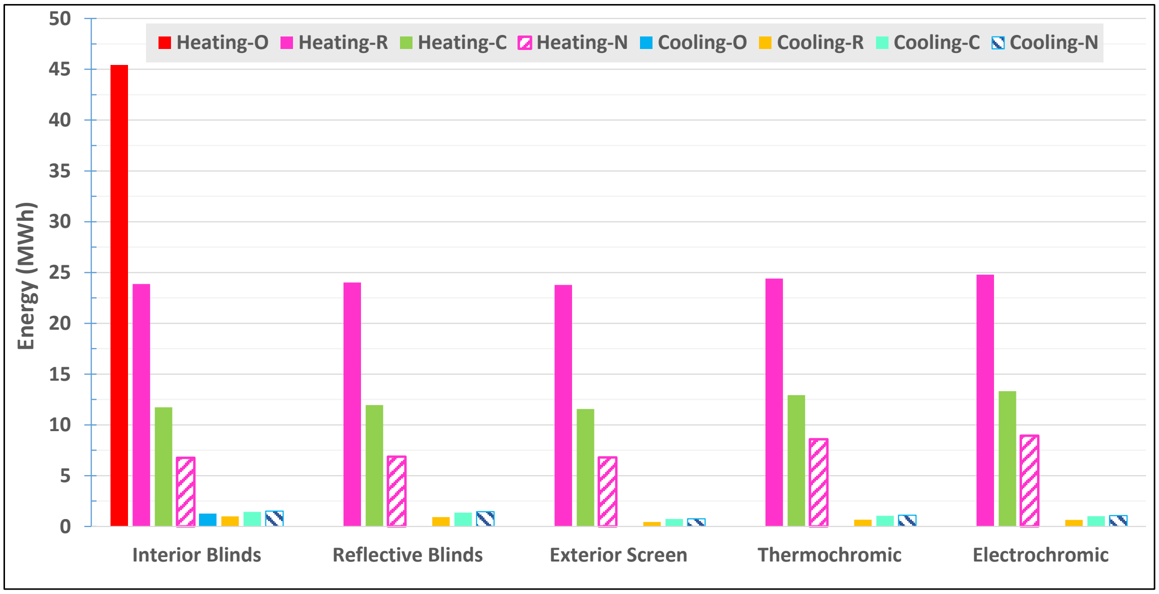


Figure 43: Effect of shading devices on annual energy use for heating and cooling for row houses with typical windows and four light constructions practices (old with Dclear, retrofit with Dclear+eH, current with Dclear+eH, and NZE with Tclear+eH)

12.3 Effect of house ventilation

Three ventilation strategies were assessed for overheating in row houses: (1) Natural ventilation by opening 25% of the surface areas of house windows when the indoor temperature of each thermal zone exceeds 26°C and the outdoor temperature; (2) Nighttime ventilation by operating the home exhaust fans (kitchen and bathrooms) and increasing their airflow rates to10 times of their nominal airflow rate (i.e., 220 litre/s or 466 CFM) from 10:00 PM to 9:00 AM; and (3) mixed mode, natural ventilation + nighttime ventilation. The strategy of using personal fan ventilation applied to single-detached homes is also applicable to row houses, and is therefore not repeated here.

Figure 44 shows the effect of ventilation strategies on the severity of overheating for row houses with typical windows and four light construction practices (old, retrofit, current, and NZE). In retrofitted houses, natural or nighttime ventilation is effective to minimize or eliminate overheating risk according to the criterion of Section 6. Natural ventilation can as well minimize or eliminate overheating risk in new or NZE row houses. Furthermore, nighttime ventilation in these homes can reduce overheating risk by 68% compared to no ventilation, but this needs additional measures such as personal fan ventilation during the daytime to minimize or eliminate overheating risk. Mixed mode ventilation does not, however, produce any additional significant effect on top of natural ventilation. Figure 45 shows the effect of whole house

House ventilation

Natural ventilation is an effective strategy to minimize the risk of overheating in all row house types. Nighttime ventilation is as well effective but will need to be combined with other measures such as fan ventilation to minimize overheating risk in new or NZE houses.

ventilation strategies on the living room temperature during the summer heat wave period in 2010 for row houses having typical windows and the current light construction practice. Natural ventilation may reduce the daytime peak indoor temperatures by up to 6°C compared to no ventilation, followed by 3°C for nighttime ventilation.

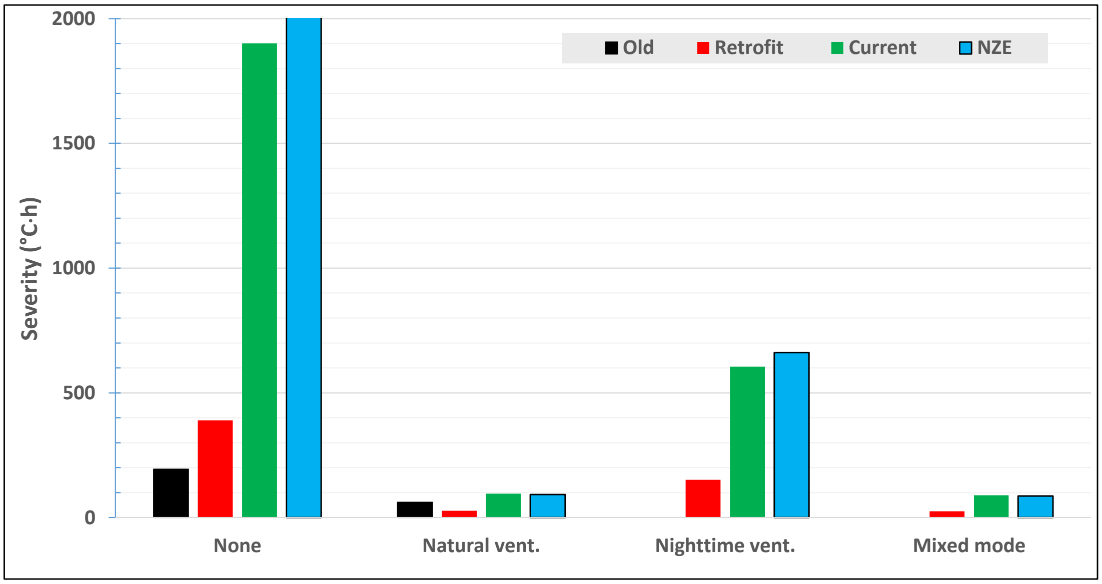


Figure 44: Effect of whole house ventilation on overheating severity for row houses with typical windows and four light constructions practices (old with Dclear, retrofit with Dclear+eH, current with Dclear+eH, and NZE with Tclear+eH)

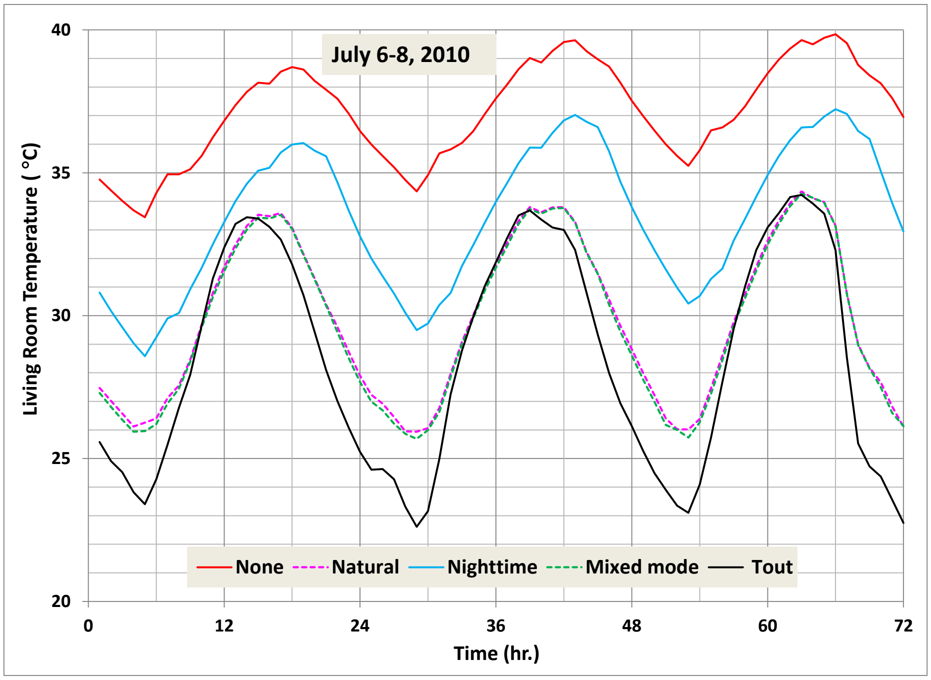


Figure 45: Effect of whole house ventilation strategies on overheating severity for row houses with typical windows and the current light constructions practice

12.4 Effect of mechanical cooling with relaxed setpoint

Figure 46 shows the effect of mechanical cooling with a relaxed (higher) setpoint temperature on overheating risk in row houses with typical windows covered by internal blinds and different local constructions practices. Relaxing the cooling setpoint temperature to 31°C (corresponding to SET = 30°C, slightly warm sensation) can effectively reduce overheating risk during extreme heat events, or eliminate it in old and retrofitted homes (severity < 230°C*h). However, minimizing or eliminating overheating risk in new or NZE row houses will need additional passive strategies such as personal fan ventilation, the opening of windows during nighttime, or use of nighttime mechanical ventilation to purge the home from excessive internal heat gains accumulated during the daytime.

Mechanical cooling

Mechanical cooling with relaxed setpoint is effective to minimize or eliminate the risk of overheating in old and retrofitted houses, but will need to be combined with other passive measures such as fan or nighttime ventilation in new or NZE houses.

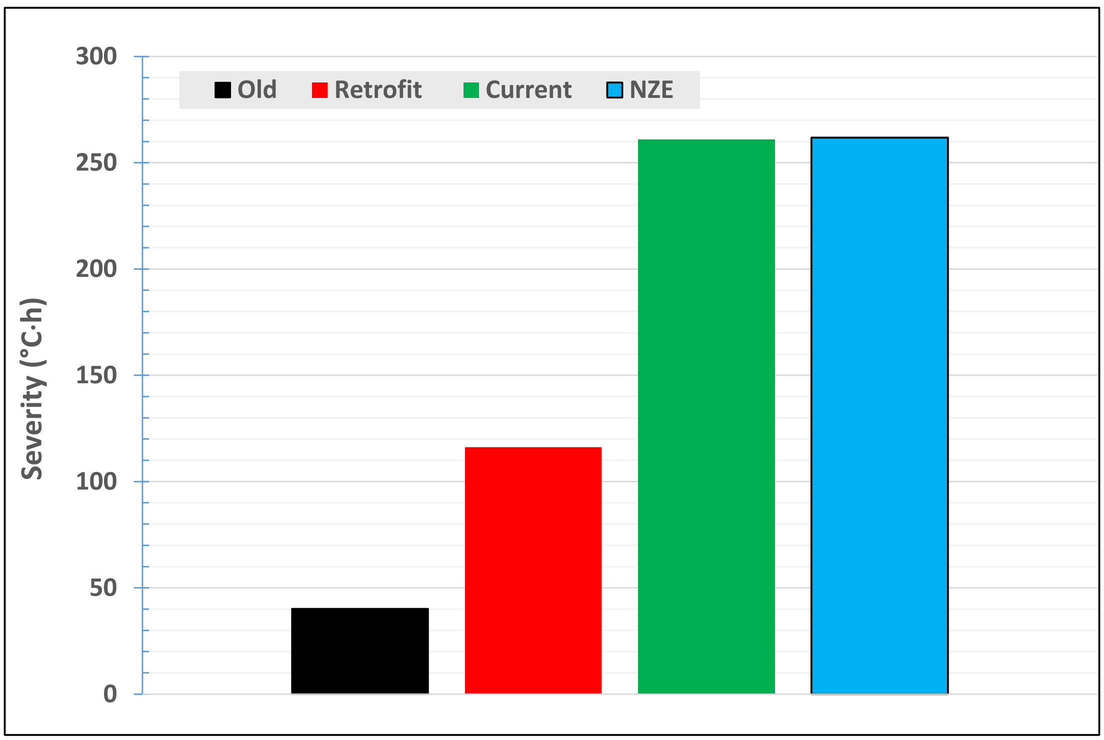


Figure 46: Effects of mechanical cooling with relaxed setpoint temperature on overheating severity for row houses with typical windows covered by internal blinds and four light constructions practices (old, retrofit, current, and NZE)

12.5 Effect of building construction types

Two types of home construction were assessed for overheating (Table 23): (1) light construction with vinyl claddings; and (2) medium construction with brick veneer cladding. Figure 47 shows the effect of construction type on the severity of overheating in homes having typical windows covered by internal blinds for local construction practices (i.e. old, retrofit, current, and NZE). To enable passive natural ventilation in those homes, windows were open if the indoor temperature exceeded 26°C and the outdoor temperature. Similar to single detached homes (Figure 32), the two types of construction have negligible effects on overheating risk. This might due to the fact that the high level of insulation behind the brick veneer (medium mass) cladding, restricts the storage of heat in the cladding mass and limits the amount of heat that reaches the interior space.

Construction types

House construction types (light or medium mass) have no significant effect on overheating risk.

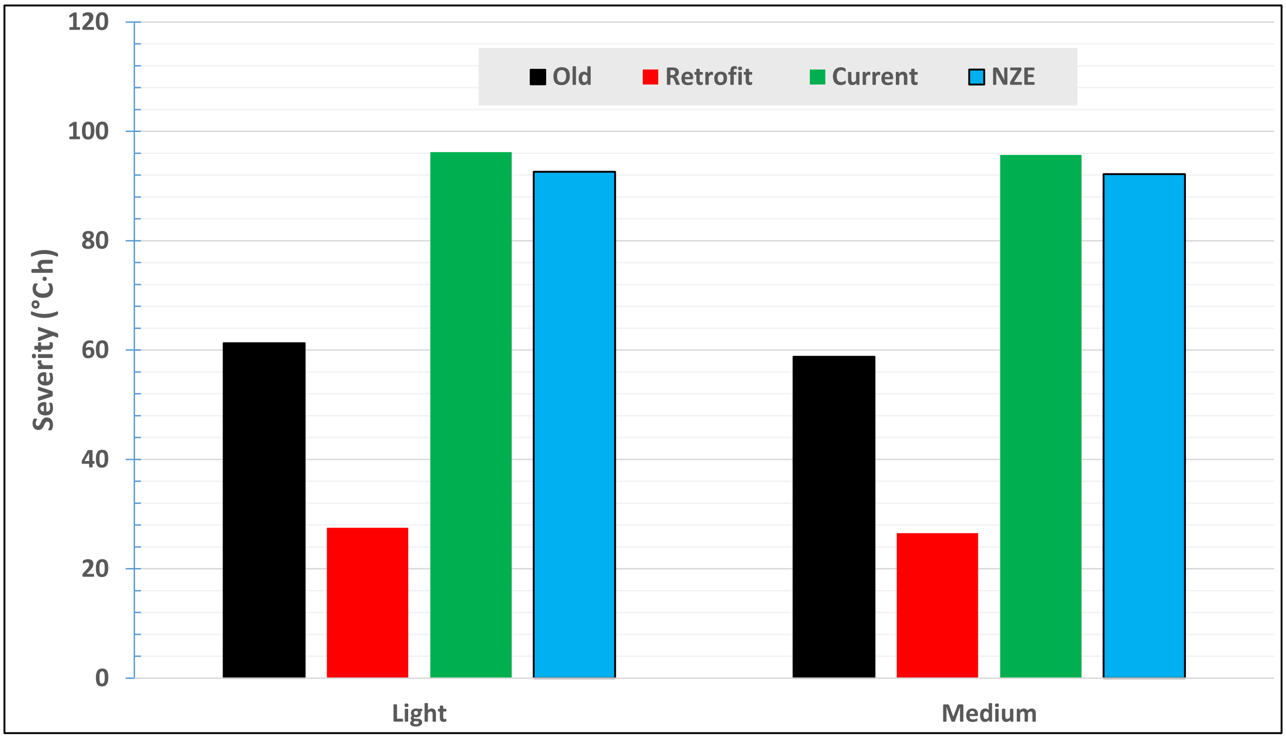


Figure 47: Effects of construction types on overheating severity in naturally ventilated row houses with typical windows covered by internal blinds and four local constructions practices (old, retrofit, current, and NZE)

12.6 House energy use and overheating risk

Figure 48 shows the relationship between the total house energy use (electric and gas) and overheating severity. The data are plotted for all home construction types that include windows covered by internal shading devices (including dynamic windows but excluding exterior shadings). Homes are assumed not naturally ventilated. It is clear that the total energy use is inversely proportional to overheating risk in airtight or naturally unventilated homes. The higher the energy efficiency requirement (or lower energy use), the higher the overheating risk. It is therefore recommended to implement passive or active measures to reduce overheating risk in new or future NZE homes, if mechanical cooling is not an option. These measures may include exterior shades with or without personal fan ventilation, natural ventilation (if windows are allowed to be opened in summer), mechanical ventilation using supply or exhaust fans, heat recovery ventilators, but with up to 10 times higher flow rates than nominal values with a summertime bypass option to avoid pre-heating the outdoor air.

Energy use & overheating

Overheating risk is inversely proportional to total energy use in airtight or naturally unventilated homes. Highly insulated homes should therefore implement passive or active measures to minimize overheating risk.

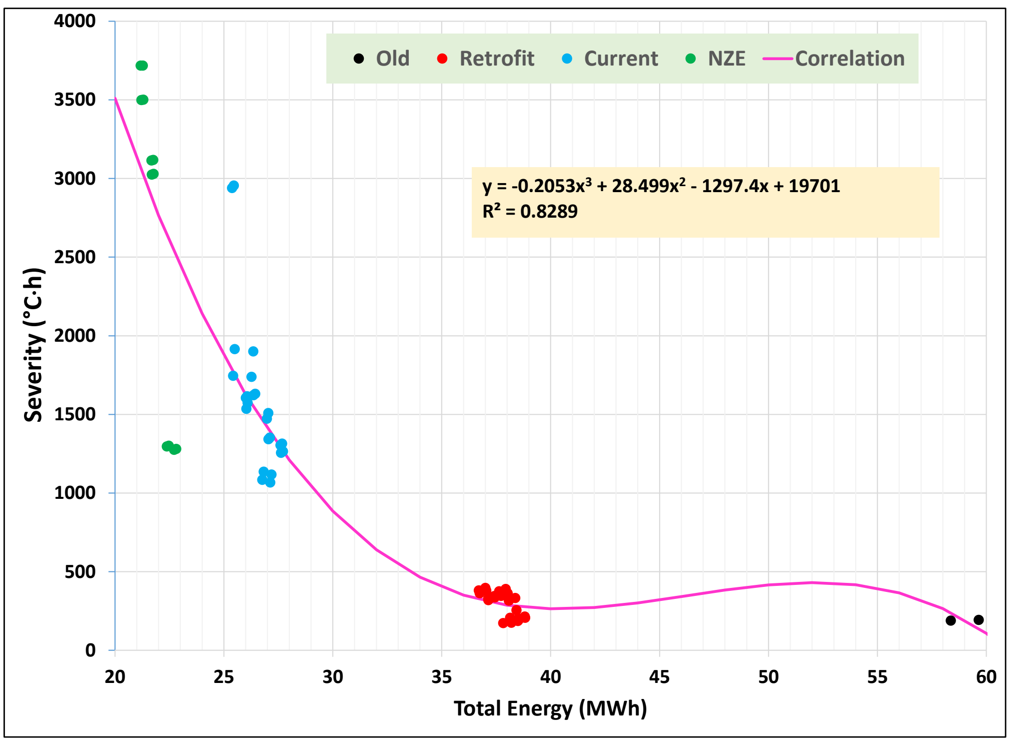


Figure 48: Relationship between total energy use and overheating risk in naturally unventilated row houses with four local constructions practices (old, retrofit, current, and NZE)

12.7 Effect of global warming on overheating risk and energy

As in the single detached houses (Section 11), simulations were conducted for seven global warming scenarios: GW0.0 (actual climate), GW0.5 (2001-2031), GW1.0 (2013-2043), GW1.5 (2024-2054), GW2.0 (2034–2064), GW2.5 (2044-2074), GW3.0 (2053-2083), and GW3.5 (2062–2092).

Figure 49 to Figure 51 show the effect of global warming degree on the severity and intensity of overheating events in retrofitted, new (current) and NZE homes, respectively, with natural ventilation being either enabled (open windows), or not enabled (closed windows). All typical windows of the homes are covered by internal blinds in summertime. The severity and intensity of overheating events increase with the global warming degree. By the end of the 21st century, the severity and intensity of overheating in retrofitted homes without natural ventilation may increase by up to 435% and 46%, respectively, compared to the current climate (GW0.0). Enabling natural ventilation in such homes may reduce overheating risk by up to 70%, and would minimize or eliminate overheating risk up to GW1.0 (2013-2043). Similarly, in new or NZE homes, the severity and intensity of overheating increase from 116% (no natural ventilation) to 3360% (with natural ventilation), and from 48% (no natural ventilation) to 400% (with natural ventilation), respectively. By the end of the global warming scenario GW1.0, natural ventilation in such houses will need to be combined with other measures to minimize or eliminate overheating risk in the next global warming scenarios.

Global warming

GW increases the severity and intensity of overheating events by up to 3360% and 400%, respectively, in naturally ventilated homes. By the end of GW1.0, new or NZE homes would need additional measures to combine with natural ventilation to minimize or eliminate the risk of overheating.

GW may reduce heating energy by up to 39% and increase cooling energy by up to 43% in new or NZE homes.

In Figure 52 the effect of global warming is shown in respect to the relative changes (with respect to GW0.0) in heating, cooling and total energy use (heating + cooling) of retrofitted, new (current) and NZE homes. Global warming decreases the heating energy use but increases the cooling energy use. By the end of the 21st century, the relative changes in the energy usage of retrofitted homes are -33% for heating and 60% for cooling. In new (or NZE) homes, the relative changes in the energy usage are -35% (-39%) for heating and 43% (37%) for cooling.

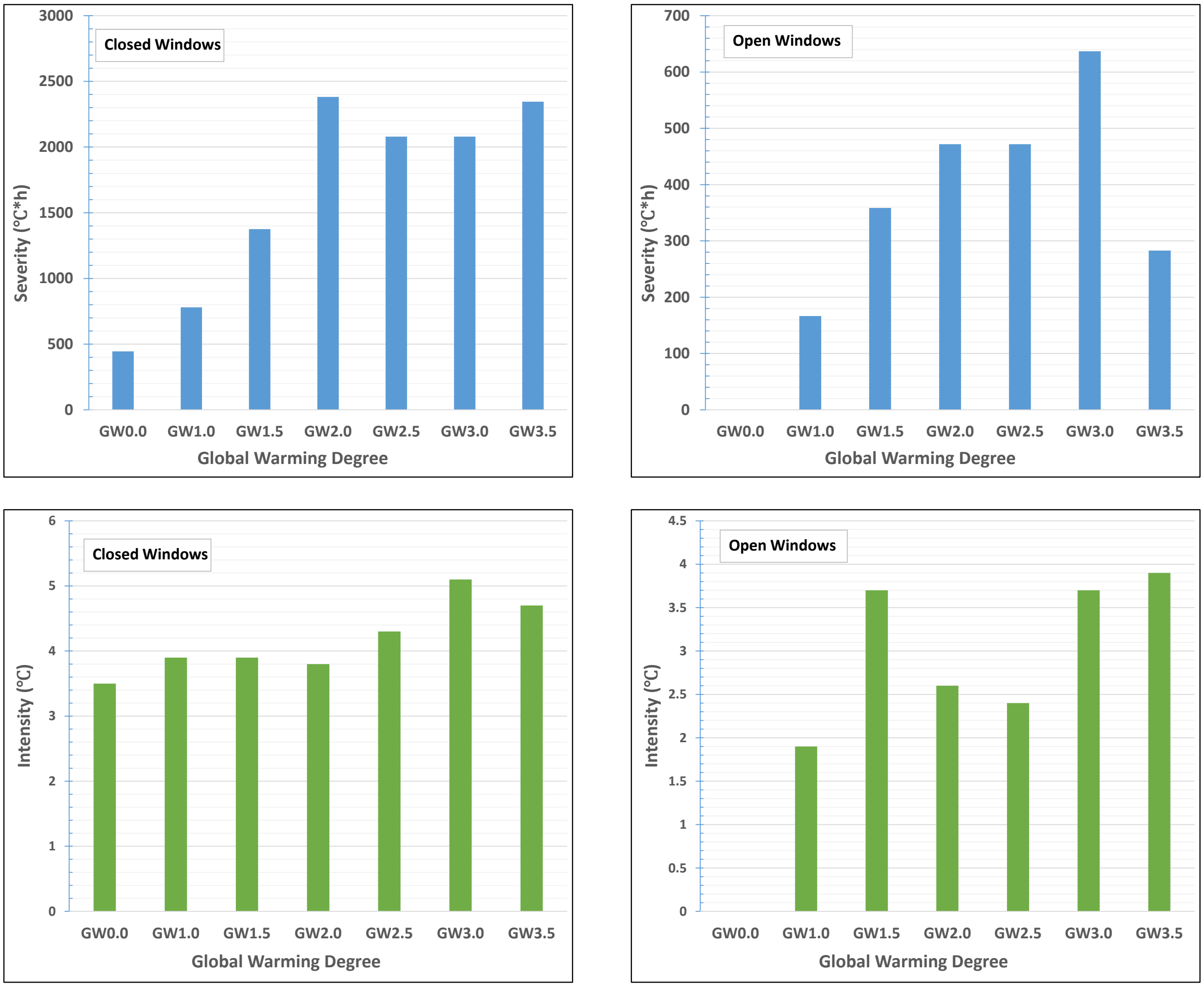


Figure 49: Effects of global warming scenarios on severity and intensity of overheating in retrofitted row house with typical windows covered by internal blinds and natural ventilation enabled (open windows) or not enabled (closed windows).

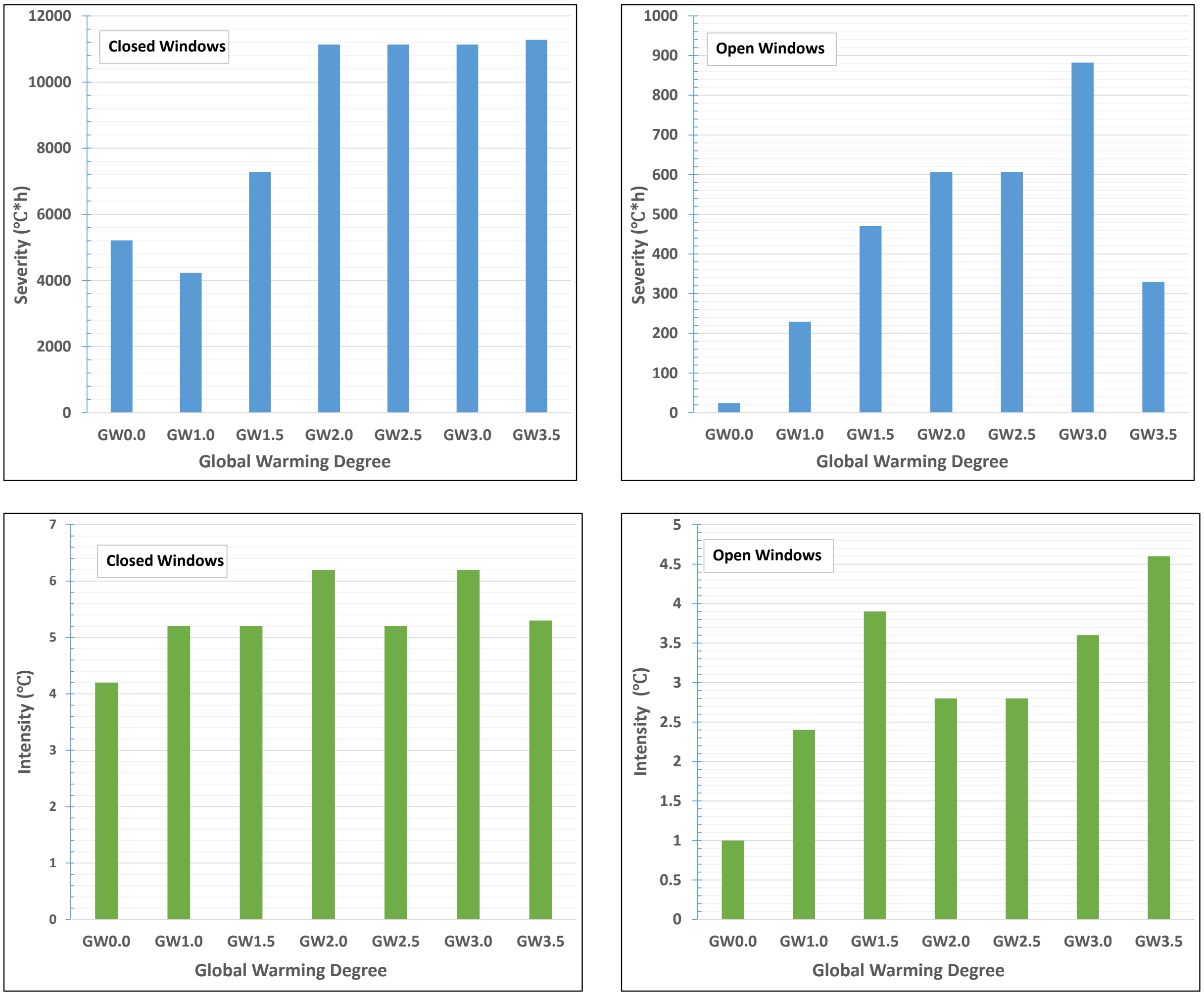


Figure 50: Effects of global warming scenarios on severity and intensity of overheating in new (current) row houses with typical windows covered by internal blinds and natural ventilation enabled (open windows) or not enabled (closed windows).

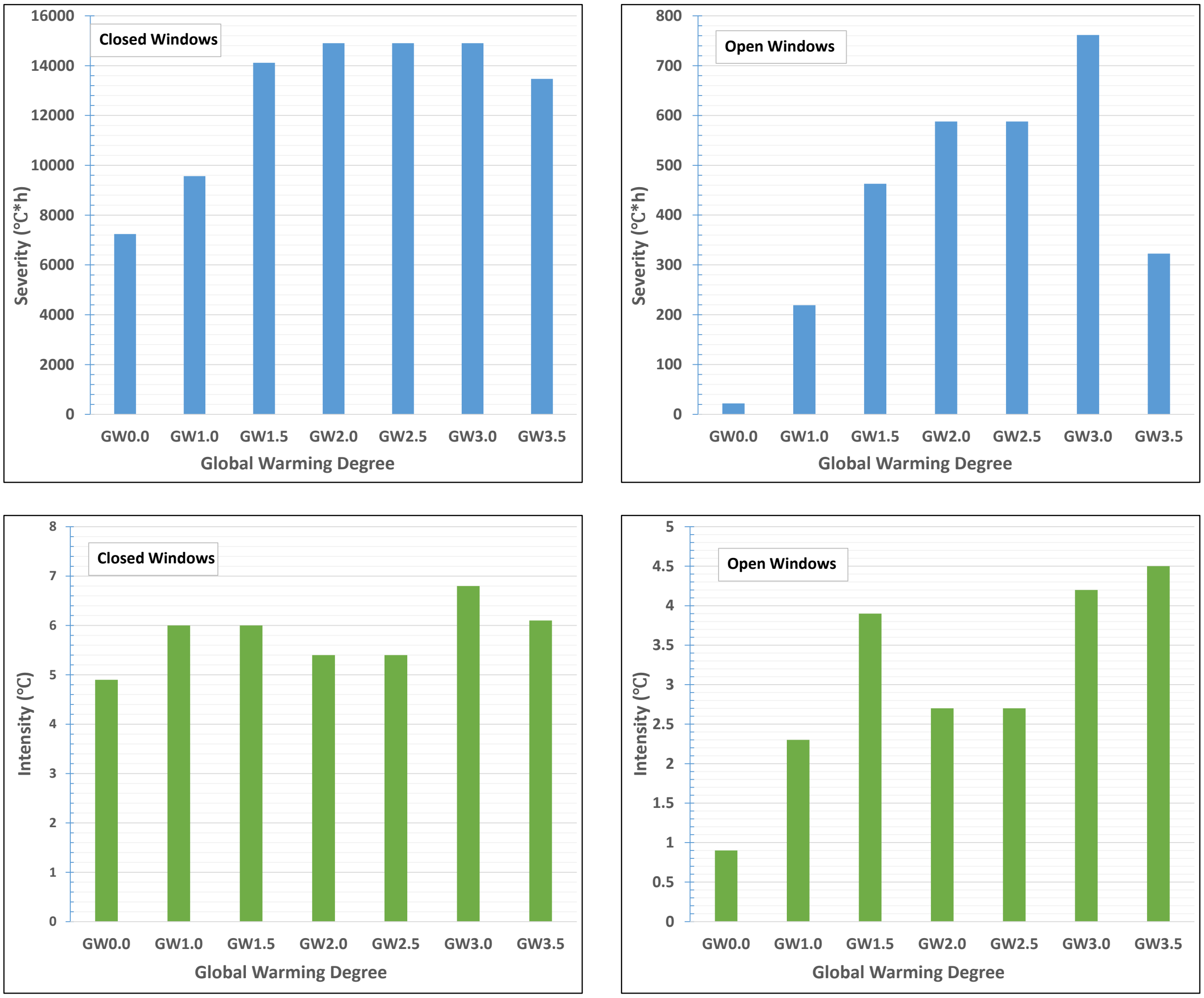


Figure 51: Effects of global warming scenario on severity and intensity of overheating in NZE row houses with typical windows covered by internal blinds and natural ventilation enabled (open windows) or not enabled (closed windows).

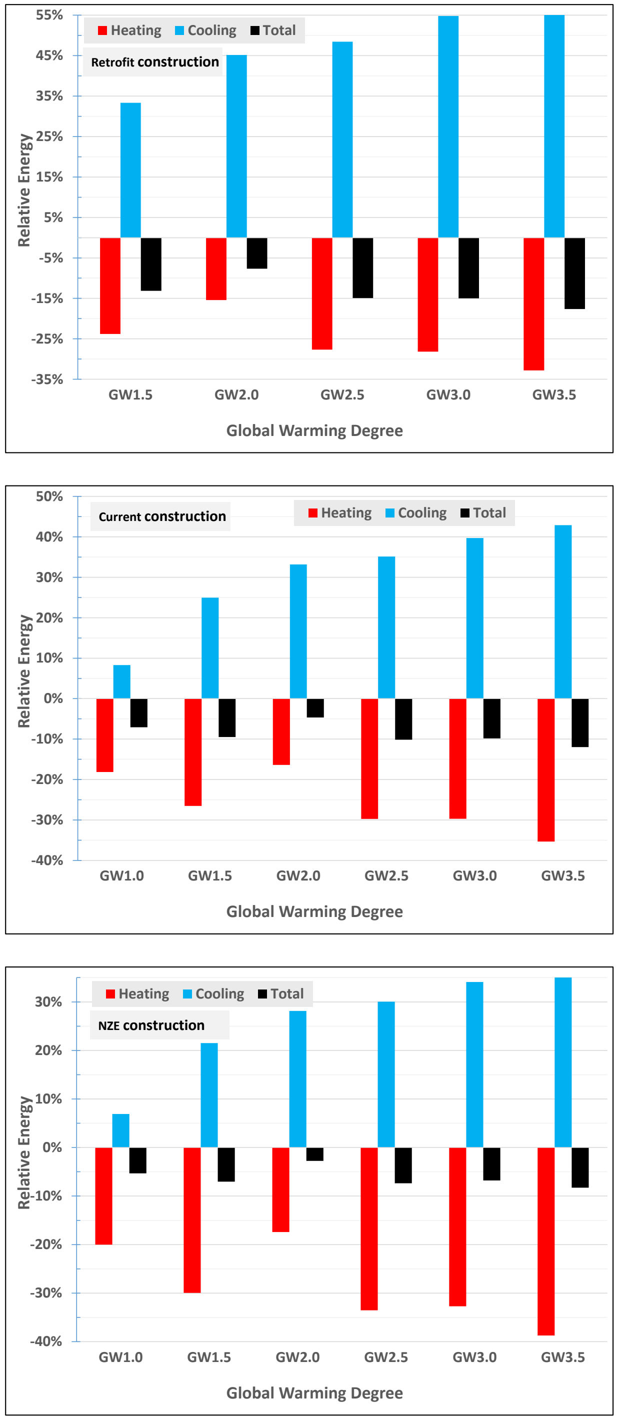


Figure 52: Effects of global warming scenarios on relative energy changes for heating, cooling and total energy of row houses with typical windows covered by internal blinds

Mid-Rise Multi-Unit Residential Buildings

Courtesy of: www.dreamstime.com

13 OVERHEATING IN MID-RISE MURB

The overheating evaluation methodology presented in Sections 6 and 9 was applied to mid-rise multi-unit residential buildings (MURB) under the current climate and future projections in Ottawa (Ontario). The mid-rise MURB is a four story building whose longest facades are oriented towards the south and north directions (Figure 79 in Appendix A). Each floor of the building is made of a series of suites separated by a central corridor space (Figure 79). Each suite space is divided into two thermal zones (living room and bedroom). Occupants are assumed dwelling in the living room space or sleeping in the bedroom space during nighttime. On the first floor, one east end suite unit (SE, Figure 79) is converted to two office spaces occupied only during daytime. This office space is not considered for overheating analysis. An interior stairway space connects the floors vertically.

The building simulation procedure was used to obtain the results of overheating in the archetypical mid-rise MURBs built according to three construction types (light, medium and high mass) and four local construction practices: old (1980s), retrofitted according to the requirements of the current national building code (NBC) (NRC, 2015), current (or new) according to the NBC, and future net zero energy (NZE) (with 30% increase in insulation levels of building envelopes). Details on the simulation model are presented in Appendix A. In the following sections the results of overheating are presented for the selected measures as described in Section 10.

13.1 Effect of window types

Figure 53 shows the maximum overheating severity in all MURB suites calculated under the current climate for various window types (Table 22) and different light construction practices (i.e. old, retrofit, current, and NZE). The windows are assumed closed and covered by internal blinds during summertime. According to the criteria of overheating in Section 6, all or some of the MURB suites excessively overheat (severity >> 230 °C·h). The west end corner suites (SW), particularly at the fourth floor, are under the highest risk of overheating, whereas suites facing the north direction (N1, N2) of the first floor are under the lowest risk of overheating. Furthermore, overheating risk increases with the building floor height (more details provided in Figure 62 to Figure 65). Overheating risk is affected by local construction practice. More specifically, old and leaky MURBs have significantly lower risk of overheating, followed by retrofitted or new MURBs, and future NZE MURBs. Windows that have low SHGC result in a lower risk of overheating, but overheating cannot be eliminated using solely this measure. Green tinted double glazed windows with low solar heat gain, low-e coatings (Dgreen+e; SHGC = 0.30) provides the best measure for risk reduction, which can reduce overheating risk by 29% as compared to double clear high solar heat gain, low-e windows (Dclear+eH; SHGC = 0.67), followed by 20% of double clear low solar

Window effects

Select windows with low SHGC (< 0.42) and U-factor (< 1.6 $W/m^2.C$) to reduce both heating energy and risk of overheating, particularly in MURB with limited natural ventilation (windows remain mostly closed in summer).

heat gain, low-e windows (Dclear+eL; SHGC = 0.42). Ironically, triple clear windows with high solar heat low-e (Tclear+eH; SHGC = 0.57) result in the highest risk of overheating, particularly when used in NZE MURBs.

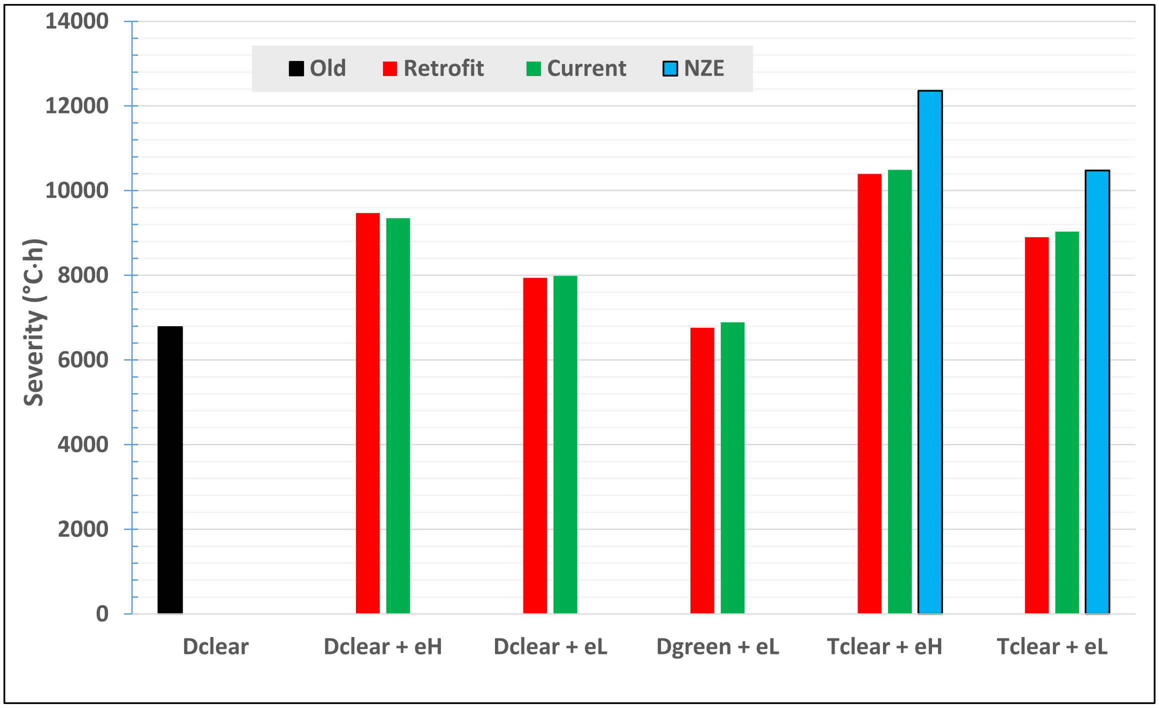


Figure 53: Effect of window types covered by interior blinds on the maximum overheating severity in suites of MURB with four light constructions practices (old, retrofit, current, and NZE)

Figure 54 shows the effect of window types covered by internal blinds on living room temperatures of the west end corner suite (SW) of the fourth floor during the summer heat wave period in 2010 for MURBs having the current light construction practice. Windows with low SHGC values (such as Dgreen+eL and Dclear+eL) may reduce the peak indoor temperatures by up to 2.9°C. Windows with high SHGC values (Dclear+eH, Tclear+eH) result in the highest peak indoor temperatures (43.7°C).

Figure 55 shows the effect of window types covered by internal blinds on the annual energy use for heating and cooling of MURB. Cooling energy use represents a small portion (< 9%) of heating energy use. Windows should therefore be selected to minimize both heating energy and overheating risk. In contrast to overheating, triple clear windows with high solar heat low-e coatings (Tclear+eH) result in the lowest heating energy use (about 12% compared to Dclear+eH). Furthermore, windows with low SHGC (Dgreen+eL and Dclear+eL) result in slightly higher (4%) heating energy use. MURB windows should be selected to have low values of SHGC (< 0.42) and centre-of-glass U-factor (< 1.6 W/m^{2}C), particularly in MURB with limited use of natural ventilation (i.e. windows remain closed during summertime heat events).

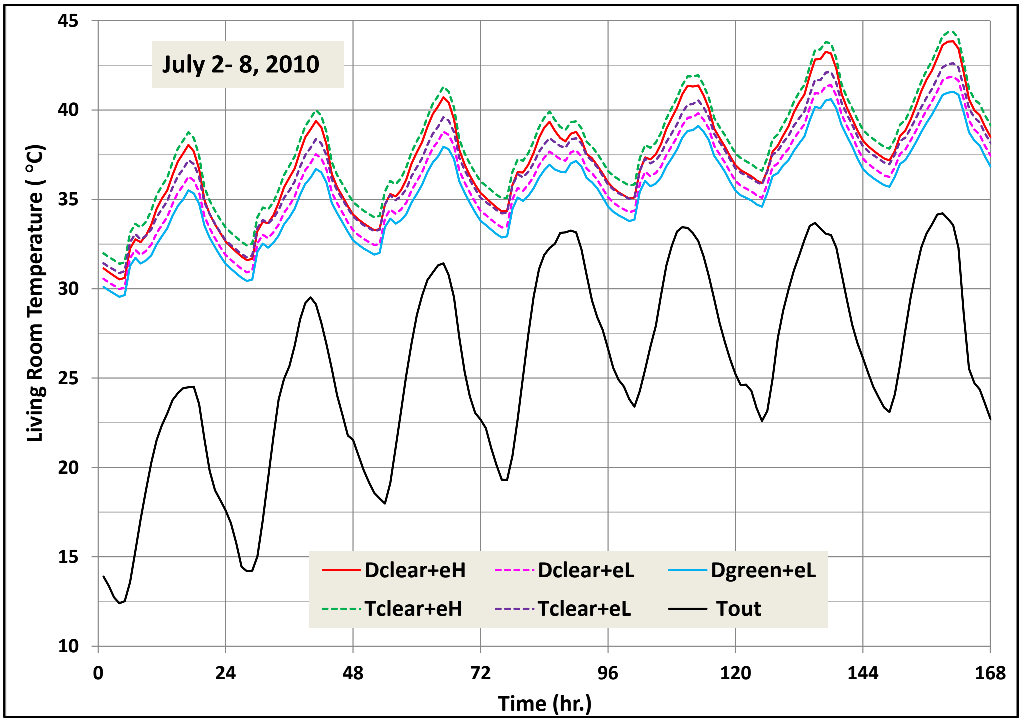


Figure 54: Effect of window types covered by internal blinds on the living room temperature of the west end corner suite (SW) of the fourth floor during the summer heat wave period in 2010 for MURB with the current light construction practice

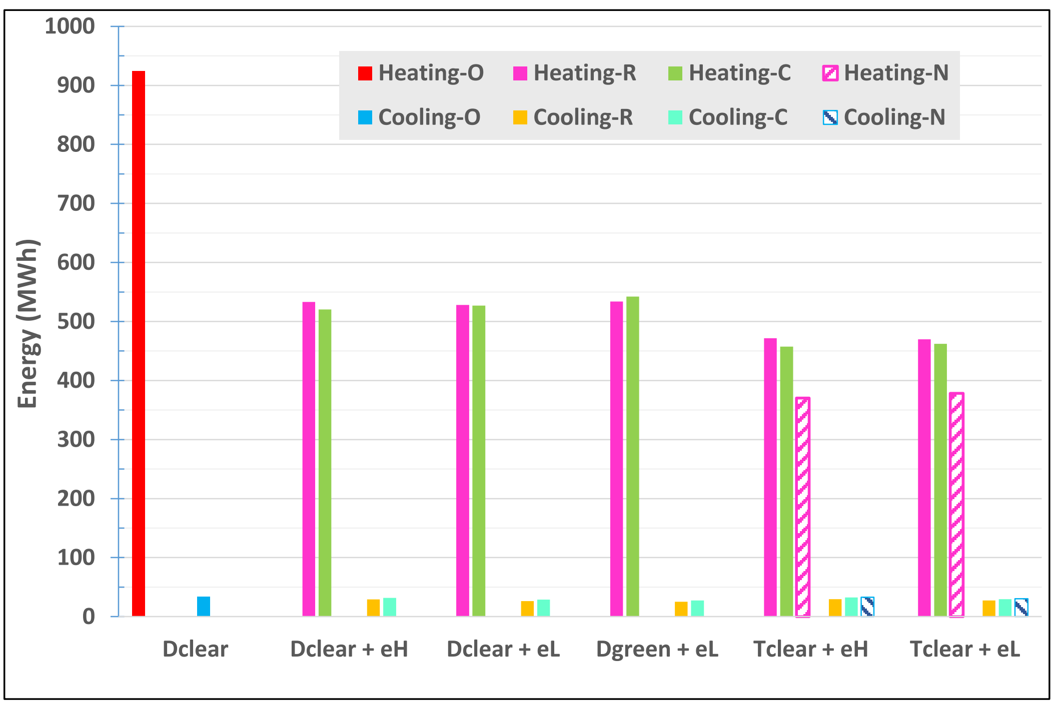


Figure 55: Effect of window types covered by internal blinds on annual energy use for heating and cooling of MURB with light constructions practices (old, retrofit, current, and NZE)

13.2 Effect of solar shading devices

Figure 56 shows the maximum and minimum values of overheating severity in suites as were calculated under the current climate for various types of shading devices (Table 21) for MURBs having typical windows and following light construction practices (i.e. old, retrofitted, current and NZE). The shading devices were assumed closed during the summertime and otherwise open. The maximum values of overheating severity occur in suites of the fourth floor whereas the minimum values occur in suites of the first floor (see Figure 62 to Figure 65). As expected, exterior shading devices are the most effective, followed by electrochromic windows, thermochromic windows, and reflective interior blinds. Compared to typical internal blinds, exterior shading devices may reduce the risk of overheating by more than 76%, followed by 60% for electrochromic windows, 42% for thermochromic windows, and 5% for internal reflective blinds. In old or retrofitted MURBs, exterior shading devices and dynamic windows (electro or thermo-chromic) may eliminate overheating risk in some suites, particularly those located at the ground floor. In new or NZE MURBs, shading devices would need to be combined with other measures, such as whole suite ventilation, to minimize overheating risk. However, dynamic windows may result in more heating energy use as is discussed next.

Shading effects

Select exterior shadings or dynamic windows to minimize overheating risk in some suites of retrofitted MURB. In new or NZE MURB, exterior shadings or dynamic windows should be combined with other measures such as whole suite ventilation to minimize overheating risk. However, dynamic windows may increase heating energy use by 20%.

Figure 57 shows the effect of shading devices on the living room temperature of the west end corner suite (SW) of the fourth floor during the summer heat wave period in 2010 for MURBs having typical windows and the current light construction practice. Exterior shadings may significantly reduce the peak indoor temperature by up to 7°C compared to internal blinds, followed by 5.5°C for electro or thermo-chromic windows.

Figure 58 shows the effect of shading devices on annual energy use for heating and cooling of MURBs. Conventional (interior and exterior) shading devices primarily reduce the cooling energy use in the summer but have non-significant effects on heating energy use of MURBs in winter. However, dynamic windows of NZE MURBs may increase the heating energy use by 20% compared to the use of internal blinds due to their lower SHGC (< 0.41).

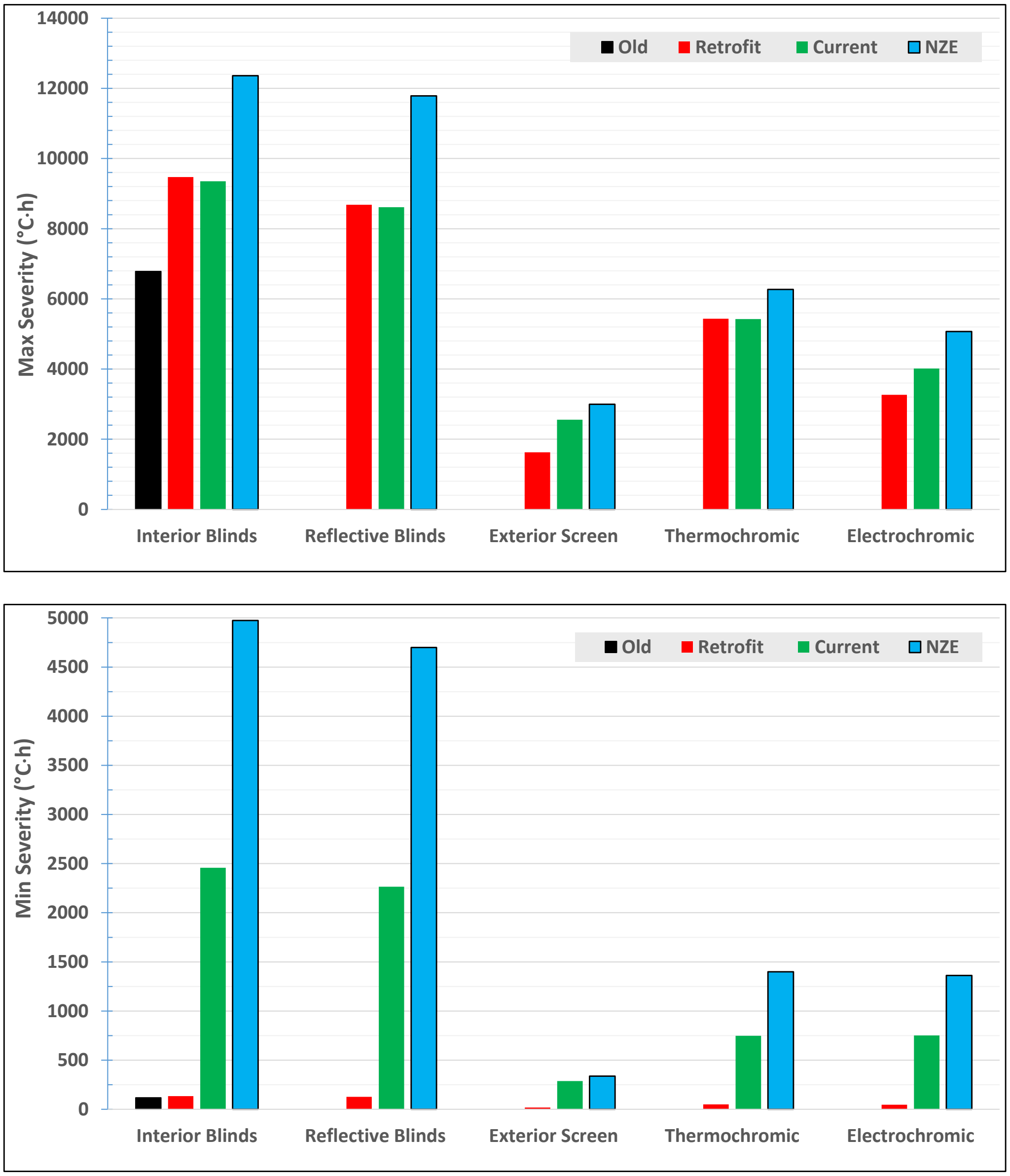


Figure 56: Effect of shading devices on overheating severity (max and min values) in MURB suites with typical windows and four light constructions practices (old with Dclear, retrofit with Dclear+eH, current with Dclear+eH, and NZE with Tclear+eH)

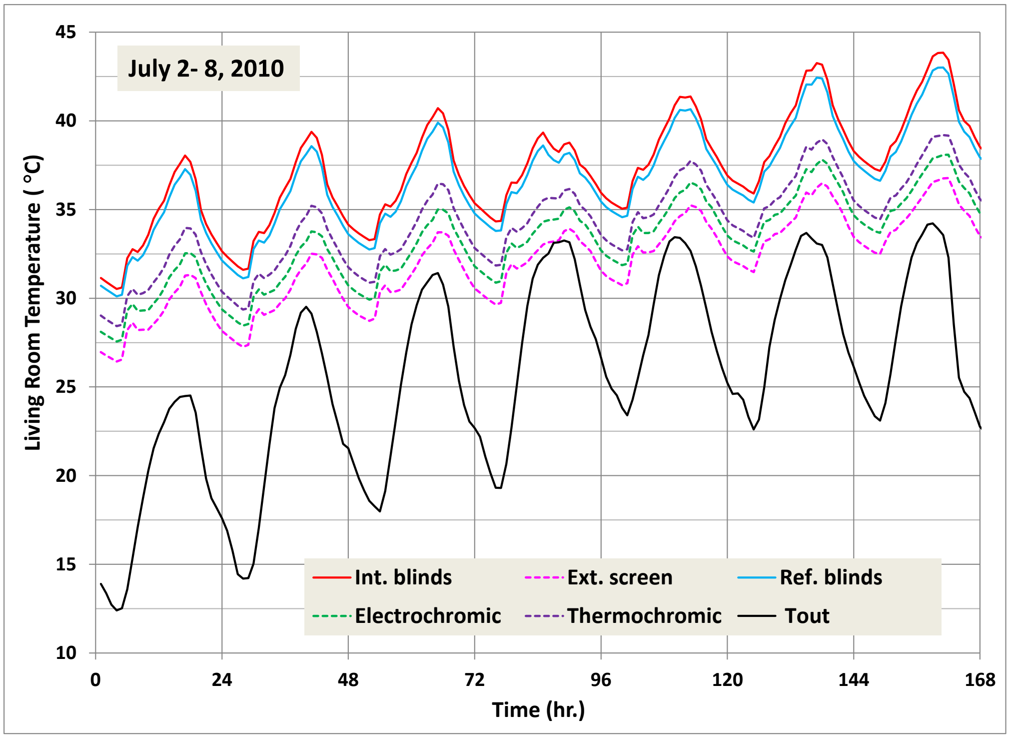


Figure 57: Effect of shading devices on the living room temperature of the west end corner suite (SW) of the fourth floor during the summer heat wave period in 2010 for MURB with typical windows (Dclear+eH) and the current light construction practice

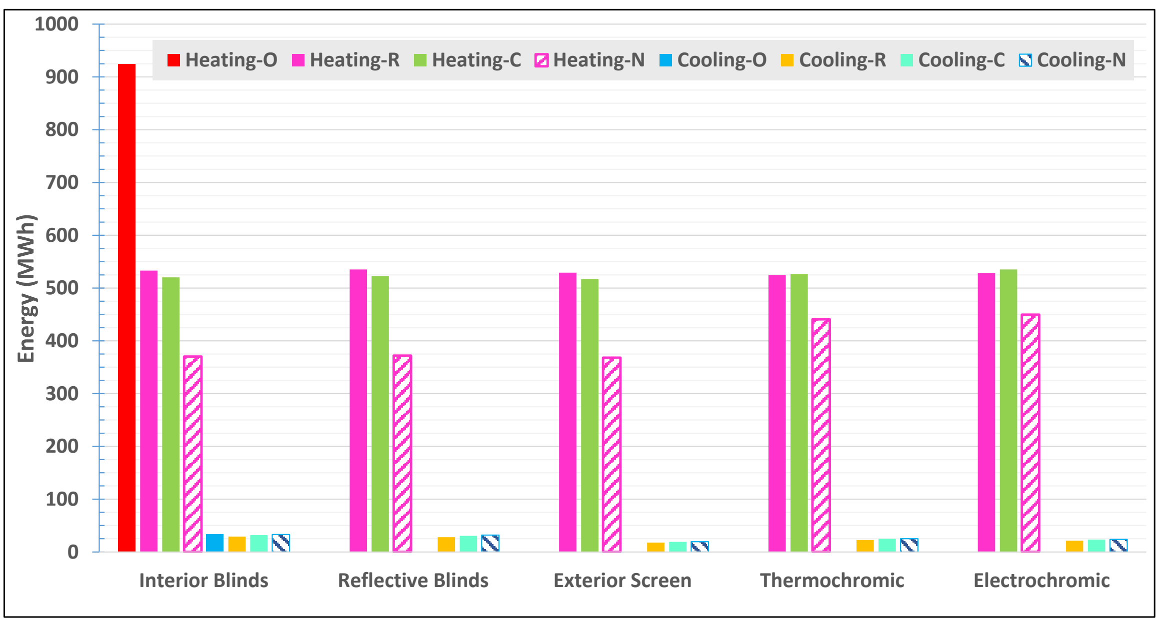


Figure 58:: Effect of shading devices on annual energy use for heating & cooling of MURB with typical windows & four light constructions practices (old, retrofit, current, and NZE)

13.3 Effect of suite ventilation

Three ventilation strategies were assessed for overheating analysis in MURBs: (1) Natural ventilation, by opening windows when the indoor temperature of each thermal zone exceeds 26°C and the outdoor temperature; (2) Nighttime mechanical ventilation; and (3) mixed mode, natural ventilation + nighttime ventilation. To be able to calculate and balance the air flow rates in the different suite thermal zones, natural and exhaust fan ventilation are integrated with the air flow network of the entire MURB.

Window opening in MURBs is usually regulated by local jurisdictional laws. In Ontario, windows that are two meters above ground and not having balconies are to be equipped with an opening restriction mechanism to limit the window opening to 100 mm (www.toronto.ca/311/knowledgebase/kb/docs/articles/municipal-licensing-and-standards/investigation-services/bylaw-enforcement-window-safety-latches.html). In this regard, windows of bedrooms are assumed opened by 10%. However, the patio door of the living room is set to 50% openness.

Nighttime ventilation in suites can be accomplished by two means: (1) Operating the exhaust fans (bathroom and kitchen) at their maximum capacity; or (2) Using the heat recovery ventilators (HRV) of suites, if so equipped. For the ventilation to be effective, the ventilation flow rates need to exceed the space ventilation requirement by the applicable building codes or ventilation standards. Furthermore, using the HRV for nighttime ventilation will require enabling the summertime bypass option if available (in Canada, this option is not provided in commercial HRVs) to avoid pre-warming the ventilation air.

Figure 59 shows the effect of the ventilation flow rate of suite exhaust fans on the bedroom temperature during nighttime ventilation from 10:00 PM to 9:00 AM (this is an optimized schedule). The fan flow rate is increased by up to 10 times the required flow rate for the suite (24 litre/s or 50 CFM for three occupants). A fan flow rate of 10 times (or 500 CFM) can induce a significant drop in the bedroom temperature by up to 6°C at 6:00 AM and 3°C at the daytime peak temperature.

Nighttime ventilation

Install powerful exhaust fans (10x required ventilation rate) in old or retrofitted MURB to induce significant cooling effect (6°C) during nighttime. In new or NZE MURB, use HRV with summertime bypass option with powerful fans (10x nominal flow rate).

As shown in Figure 60, the nighttime ventilation using exhaust fans and HRV is compared with a flow rate of 10 times the required ventilation rate for the suite. The HRVs are assumed running continuously (24h/7 days) whereas exhaust fans are operated daily from 10:00 PM to 9:00 AM. Two options for operating HRVs were assessed: with and without the summertime bypass option. Exhaust fans and HRV with a bypass option can produce roughly the same cooling effect for the indoor temperature. However, a HRV without a bypass option (regular operation at 60% heat recovery efficiency) is less effective in cooling the indoor space. In this guideline document, nighttime ventilation using suite exhaust fans with 10 times the required flow rate is used as a basis for comparison with other ventilation strategies.

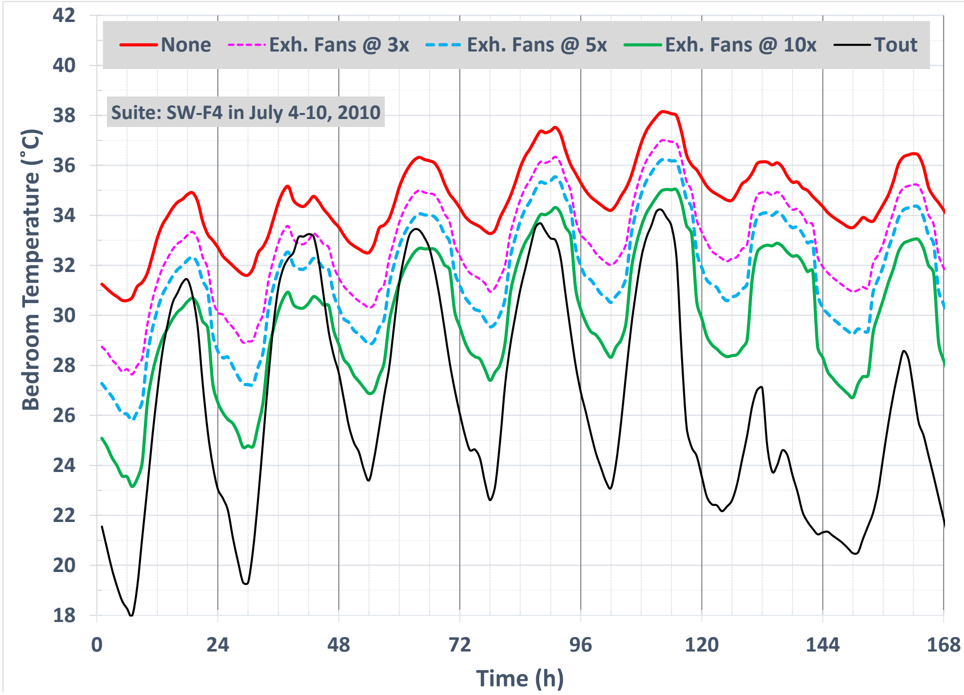


Figure 59: Effect of flow rate of suite exhaust fans during nighttime ventilation (10 PM to 9AM) on MURB (current light construction practice) bedroom temperature of 4th floor west end corner suite (SW) during heat wave period in 2010

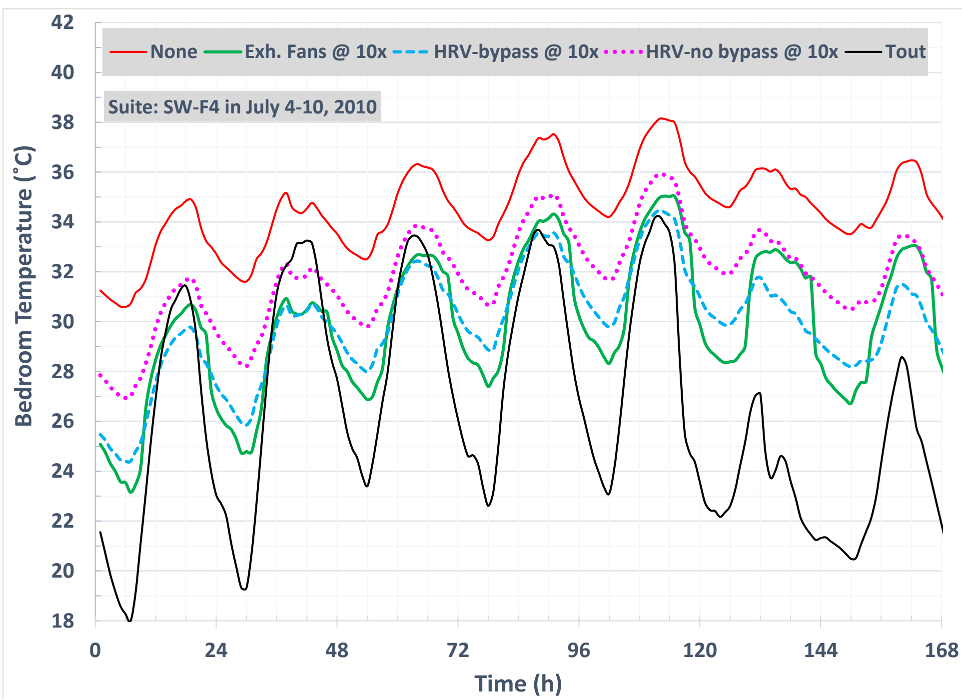


Figure 60: Comparison of nighttime ventilation using HRV (continuous) and exhaust fans (10PM to 9AM) on MURB (current light construction practice) for 4th floor bedroom temperature of west end corner suite (SW) during the heat wave period in 2010

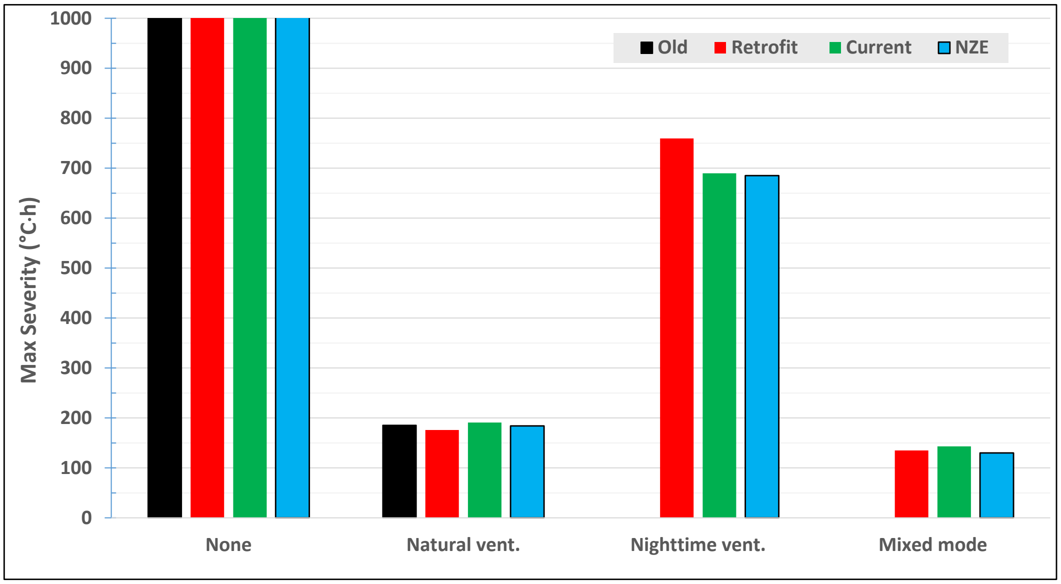
Figure 61 shows the effect of the ventilation strategies on overheating severity (min and max values) in suites of MURBs with typical windows covered by internal blinds and for different light construction practice (i.e. old, retrofit, current, and NZE). Natural ventilation is effective in minimizing or eliminating overheating risks (max severity < 230°C*h) in all suites of the different MURB types. Nighttime ventilation in retrofitted, new or NZE MURBs can minimize or eliminate overheating risk in some suites, particularly at the lower floors, but this approach needs to be combined with other measures (e.g. exterior shades) for suites located in the upper floors. Mixed mode ventilation does not, however, produce any additional significant effect over and above that of natural ventilation.

Suite ventilation

Natural ventilation can minimize or eliminate overheating risk in all MURB suites. Nighttime ventilation is effective in suites of lower floors, but will need to be combined with other measures in suites of upper floors.

Figure 62 to Figure 65 show spatial maps of overheating severity in suites with/without natural ventilation for old, retrofitted, new, or NZE MURBs, respectively. For old MURBs without natural ventilation, all suites overheat, except the ones on the first floor, which exhibit lower or slightly higher severity values than the threshold value. Suites at the upper floors are under a higher overheating risk than those of the lower floors. However, when natural ventilation is enabled, all MURB suites are under minimum or no overheating risk according to the proposed criterion for overheating. Similarly, for retrofitted MURBs without natural ventilation, all suites are overheated, except some suites of the first floor (west end corner suites (SW, NW) are not overheated. Natural ventilation can minimise or eliminate overheating risk in all suites. However, in new or NZE MURBs without natural ventilation, all suites overheated. Using natural ventilation can again minimise or eliminate overheating risk in all suites.

For information purposes, Figure 66 shows the effect of ventilation strategies on the living room temperature of the west end corner suite (SW) of the fourth floor during the summer heat wave period in 2010 for MURBs having typical windows of current light construction practice. Natural ventilation may reduce the daytime peak indoor temperatures by up to 8°C and nighttime temperature by up to 10°C as compared to no ventilation, followed by 5.5°C and 9.5°C for nighttime ventilation. Figure 67 shows the profile of the living room temperature of the south suite (S1) as a function of the building floor. Suites of the upper floor are about 3°C warmer than the first floor during daytime.



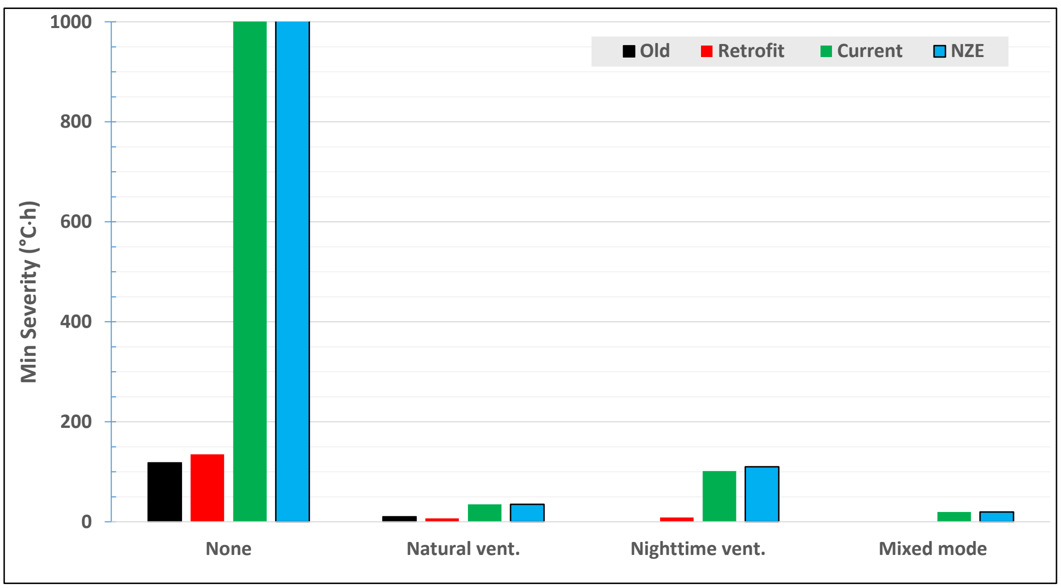


Figure 61: Effect of ventilation strategies on overheating severity (max and min values) in MURB suites with typical windows covered by internal blinds and four light constructions practices (old, retrofit, current, and NZE)

Severity	0 - 50	51 - 100	101 - 150	151 - 200	201 - 250	251 - 300	> 301

Without natural ventilation				With natural ventilation			
NW 4408	N1 2709	N2 2706	NE 3147	NW 176	N1 157	N2 158	NE 178
Corridor: F4				Corridor: F4			
SW 4990	S1 4464	S2 4458	SE 4466	SW 186	S1 174	S2 174	SE 179
3102	2571	2551	2433	161	145	145	163
Corridor: F3				Corridor: F3			
3231	2673	2653	2486	161	147	148	156
1807	1291	1285	1330	128	111	111	134
Corridor: F2				Corridor: F2			
1859	1513	1497	1288	127	114	114	128
256	140	141	203	46	15	15	51
Corridor: F1				Corridor: F1			
263	148	146	22	46	16	16	0

Figure 62. Maps of overheating severity without and with natural ventilation in suites of MURB with old constructions

Severity	0 - 50	51 - 100	101 - 150	151 - 200	201 - 250	251 - 300	> 301

Without natural ventilation

NW	N1	N2	NE
7220	4975	5008	5366
Corridor: F4			
SW	S1	S2	SE
9436	7251	7234	7569
5423	4919	4885	4893
Corridor: F3			
7282	6822	6781	6490
2863	2086	2064	2127
Corridor: F2			
2983	2147	2120	2079
452	167	167	245
Corridor: F1			
467	176	174	29

With natural ventilation

NW	N1	N2	NE
168	149	149	176
Corridor: F4			
SW	S1	S2	SE
176	161	160	174
161	145	146	170
Corridor: F3			
161	148	147	160
128	112	114	140
Corridor: F2			
127	116	116	135
43	14	14	53
Corridor: F1			
43	15	14	0

Figure 63. Maps of overheating severity without and with natural ventilation in suites of MURB with retrofit constructions

Severity	0 - 50	51 - 100	101 - 150	151 - 200	201 - 250	251 - 300	> 301

Without natural ventilation

NW	N1	N2	NE
5881	5671	5647	5840
Corridor: F4			
SW	S1	S2	SE
9258	8824	8795	7932
5874	7094	7067	5786
Corridor: F3			
7876	7870	7860	7574
5117	5194	5175	4812
Corridor: F2			
5386	6781	6781	6599
3154	2514	2500	2458
Corridor: F1			
4122	2583	2579	2387

With natural ventilation

NW	N1	N2	NE
180	156	156	185
Corridor: F4			
SW	S1	S2	SE
191	175	175	185
180	153	154	184
Corridor: F3			
181	159	158	175
169	138	138	171
Corridor: F2			
170	140	140	165
128	94	94	133
Corridor: F1			
129	98	98	32

Figure 64. Maps of overheating severity without and with natural ventilation in suites of MURB with current constructions

Severity	0 - 50	51 - 100	101 - 150	151 - 200	201 - 250	251 - 300	> 301

Without natural ventilation				With natural ventilation			
NW 10829	N1 9636	N2 9577	NE 9868	NW 174	N1 153	N2 153	NE 182
Corridor: F4				Corridor: F4			
SW 11800	S1 10789	S2 10747	SE 10987	SW 182	S1 168	S2 168	SE 179
11152	10467	10410	10101	176	153	154	184
Corridor: F3				Corridor: F3			
11797	11551	11201	10969	177	158	157	175
9584	9351	9299	7766	166	139	139	172
Corridor: F2				Corridor: F2			
10282	9960	9942	9723	166	141	141	165
6206	5176	5121	4974	125	95	95	134
Corridor: F1				Corridor: F1			
6820	6675	6681	5134	126	98	97	32

Figure 65. Maps of overheating severity without and with natural ventilation in suites of MURB with NZE constructions

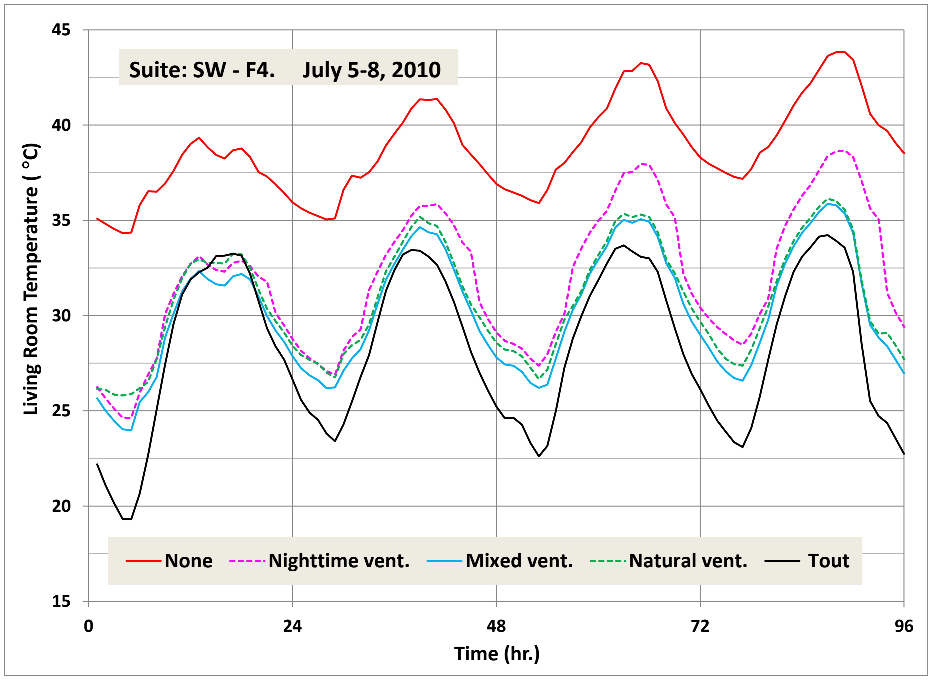


Figure 66: Effect of ventilation strategies on the living room temperature of the west end corner suite (SW) of the fourth floor during the summer heat wave period in 2010 for MURB with typical windows and the current light construction practice

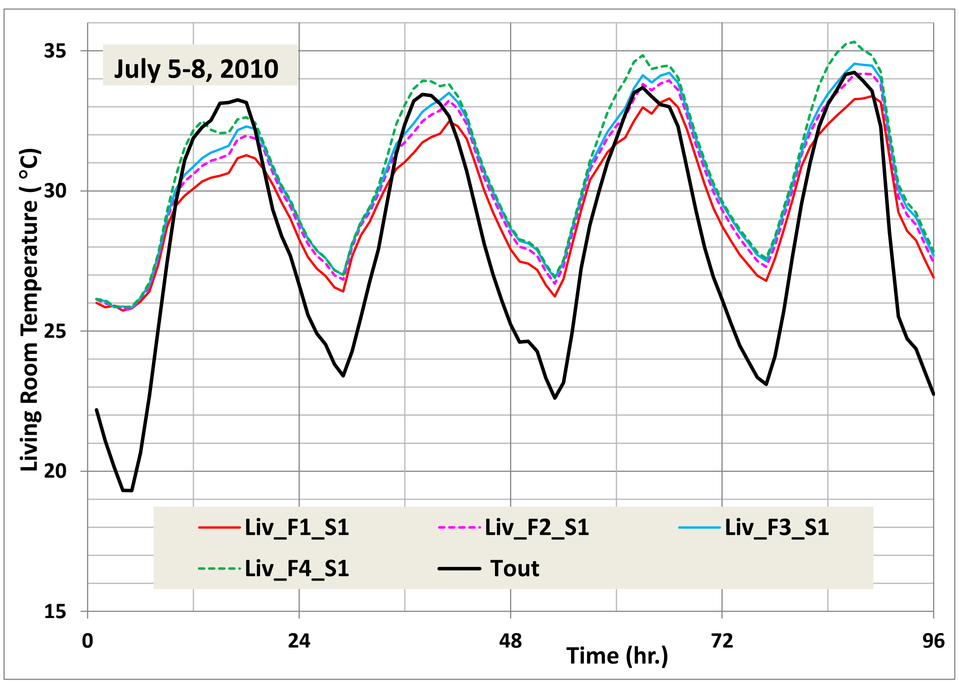


Figure 67: Profile of the living room temperature of the south suite (S1) per building floor during the summer heat wave period in 2010 for MURB with typical windows and the current light construction practice

13.4 Effect of mechanical cooling with relaxed setpoint

Operating a central cooling system or window air conditioner during extreme heat events in summer with a relaxed (higher) set point temperature is sometimes required to reduce the prohibitive cost of cooling. Furthermore, this strategy would as well benefit electric utilities in reducing the electric demand during peak hours. Figure 68 shows how this strategy affects overheating risk in suites of MURBs having different construction practices. Relaxing the cooling setpoint temperature to 31°C (corresponding to SET = 30°C, slightly warm sensation) can effectively minimize or eliminate overheating risk (severity < 230°C*h) in some suites of all MURB types during extreme heat events. Suites that experience slight overheating will require additional passive measures such as opening windows during the nighttime or using mechanical nighttime ventilation to purge the building from excessive internal heat gains accumulated during the daytime.

Mechanical cooling

Mechanical cooling with relaxed setpoint (31°C) is effective to minimise the risk of overheating in suites of all MURB types. Additional passive measures such as nighttime ventilation are needed to fully eliminate overheating risk in suites of upper floors.

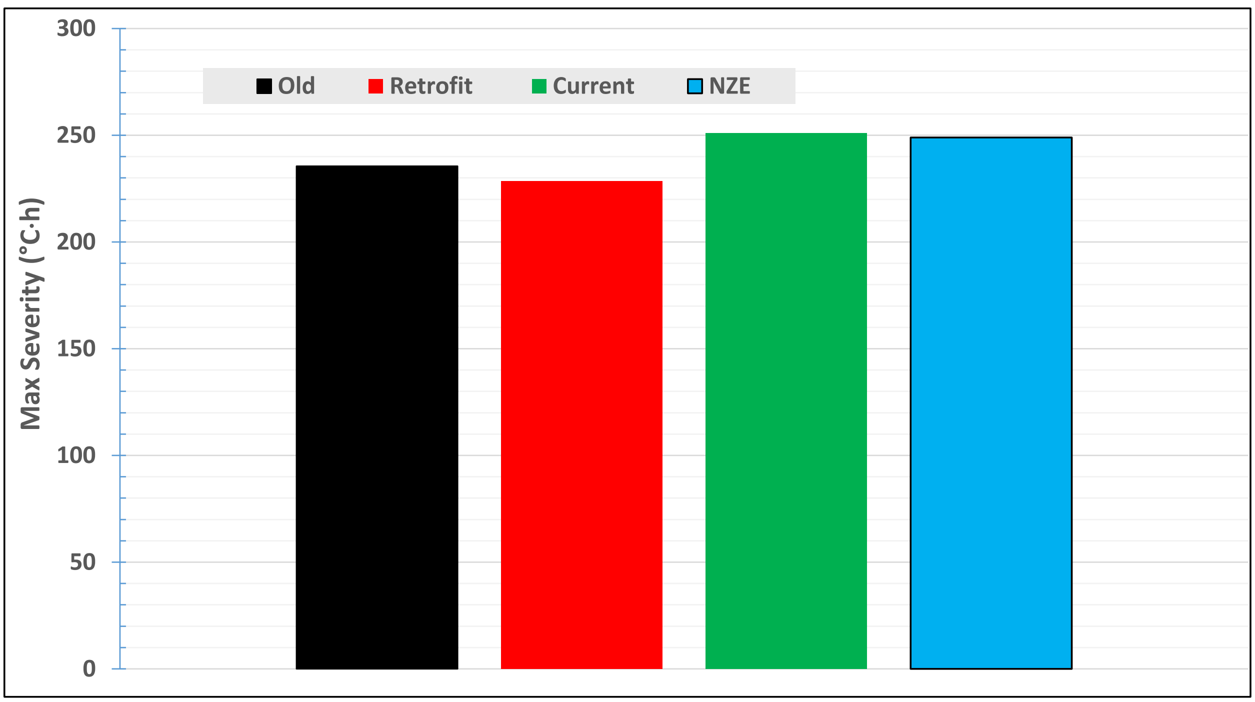


Figure 68: Effects of mechanical cooling with relaxed setpoint temperature on the maximum overheating severity in suites of MURB with typical windows covered by internal blinds and four light constructions practices (old, retrofit, current, and NZE)

13.5 Effect of building construction types

Three MURB construction types were assessed for overheating (Table 25) that include: (1) light constructions with fiber reinforced concrete panel claddings; (2) medium construction with brick veneer claddings; (3) heavy construction with fiber reinforced concrete panel claddings and externally insulated concrete walls.

Figure 69 shows the effect of construction type on the maximum severity of overheating in suites with and without natural ventilation of MURBs of different construction practice (old, retrofit, current, and NZE). MURB construction types may have a slight effect on overeating risk whether, or not, the building is naturally ventilated. Heavy construction tends to slightly reduce the risk of overheating by up to 10% compared to light or medium construction.

Construction types

Heavy constructions tend to produce slightly lower (< 10%) risk of overheating in all MURB types.

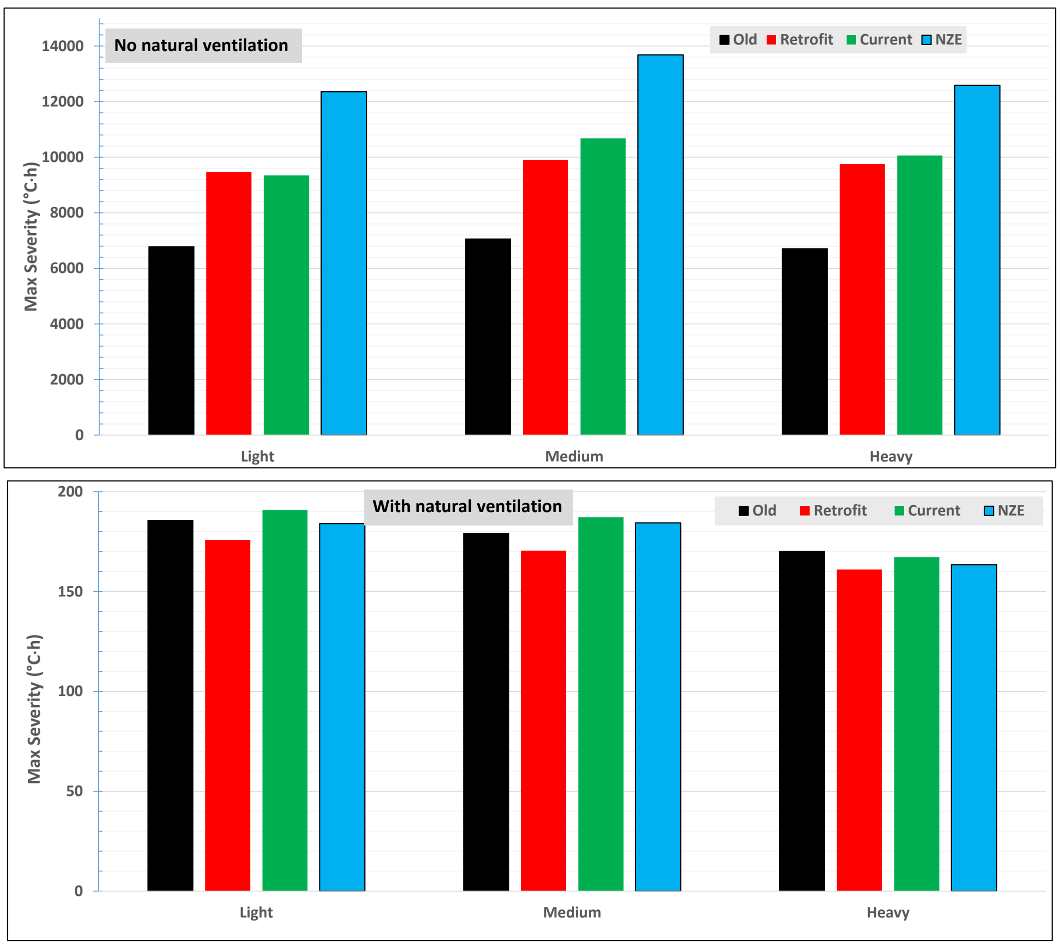


Figure 69: Effects of construction types on the maximum overheating severity without and with natural ventilated in suites of MURB with four local constructions practices (old, retrofit, current, and NZE

13.6 Effect of reflective roofs

Reflective roofs may reduce solar heat gains through the roof assembly to the indoor space below it. However, the effect of reflective roofs can be attenuated by the roof insulation level. In this guideline document, a typical solar reflectivity of 70% for MURB roofs is compared with regular roofs.

Reflective roofs

Reflective roofs of MURB slightly (< 6%) reduce overheating risk in suites directly under roofs.

Figure 70 shows the effect of reflective roofs on the maximum severity of overheating in suites with natural ventilation of MURBs with four local light construction practices (old, retrofit, current, and NZE). Reflective roofs slightly reduce (by up to 6%) overheating risk, particularly in suites directly beneath roofs.

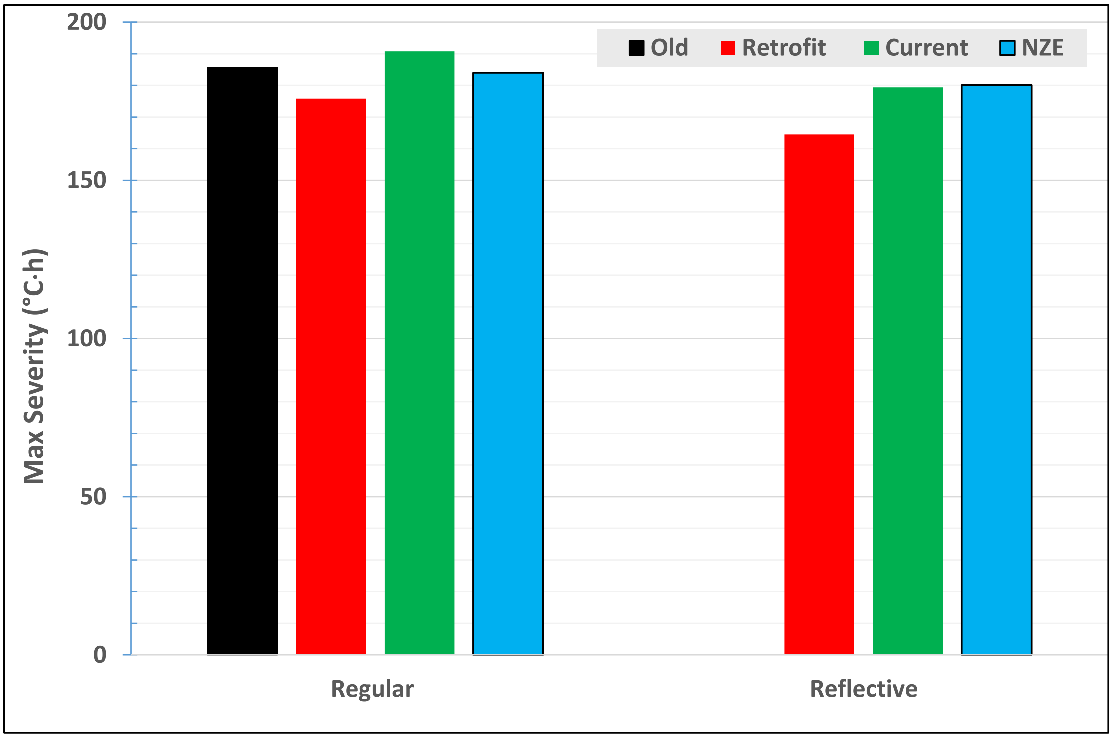


Figure 70: Effects of reflective roofs on the maximum overheating severity in naturally ventilated suites of MURB with four local light constructions practices (old, retrofit, current, and NZE)

13.7 MURB energy use and overheating risk

The relationship between total (electric and gas) energy use and overheating risk in MURBs is very important for thermal resilience designs of buildings to maintain healthy and safe environments. Requirements for high building energy efficiency has been rising in the past decades to contravene the ever-increasing effect of greenhouse gas emissions on the climate, but little has been known for the associated risk to overheating. Figure 71 shows how the total MURB energy use is related to overheating severity in suites without natural ventilation. The data are plotted for MURBs with all window types and internal shading devices, including dynamic windows (but excluding exterior shading devices). It is clear that the total energy use is inversely proportional to overheating risk in airtight or naturally unventilated MURBs. The higher the energy efficiency requirement (or lower energy use), the higher the overheating risk. It is therefore recommended that passive or active measures be implemented to reduce overheating risk in retrofitted, new or future NZE MURBs, if mechanical cooling is not an option. Those measures may include exterior shades, personal fan ventilation, natural ventilation (if windows are allowed to be opened in summer), mechanical ventilation using supply or exhaust fans, heat recovery ventilators with summertime bypass option and higher flow rates than nominal values.

Energy use & overheating

Overheating risk is inversely proportional to total energy use in airtight or naturally unventilated MURB suites. Highly insulated MURB should therefore implement passive or active measures to reduce overheating risk.

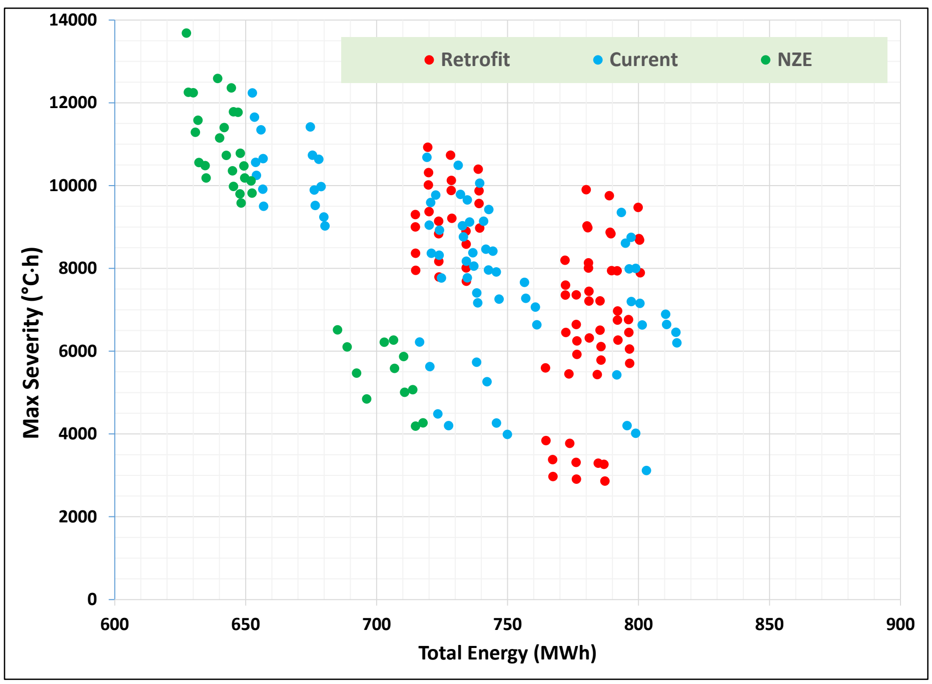


Figure 71: Relationship between building total (electric and gas) energy use and maximum overheating severity in MURB suites without natural ventilation

13.8 Effect of global warming on overheating risk and energy

Simulations were conducted for seven global warming scenarios representing global temperature changes of 0.5°C to 3.5°C. These include: GW0.0 (current climate), GW0.5 (2001-2031), GW1.0 (2013-2043), GW1.5 (2024-2054), GW2.0 (2034–2064), GW2.5 (2044-2074), GW3.0 (2053-2083), and GW3.5 (2062–2092). Figure 72 to Figure 74 show the effect of global warming degree on the maximum severity and intensity of overheating events in suites of retrofitted, new (current) and NZE MURBs, respectively, without and with natural ventilation. All MURB windows were equipped with typical internal blinds, which were assumed closed during summertime. The severity and intensity of overheating events increases with the global warming degree. By the end of the 21st century, the severity and intensity of overheating in suites of retrofitted MURB increases from 55% (no natural ventilation) to 1270% (with natural ventilation), and from 23% (no natural ventilation) to 143% (with natural ventilation), respectively, compared to the current climate (GW0.0). The noted sharp increase in overheating severity in naturally ventilated MURB suites is due to the fact that overheating events in such suites are shorter than in suites without natural ventilation. Natural ventilation can be an effective measure to minimise overheating risk but before reaching scenario GW1.0 (2013-2043). Similarly, for new or NZE MURBs, the severity and intensity of overheating increases from 50% (no natural ventilation) to 1944% (with natural ventilation), and from 25% (no natural ventilation) to 117% (with natural ventilation), respectively. Natural ventilation in these MURBs can be effective but only before reaching scenario GW1.0 (2013-2043).

Global warming

GW increases the severity and intensity of overheating events by up to 1944% and 143%, respectively, in naturally ventilated MURB. Natural ventilation is effective to minimize overheating risk in all MURB types but before reaching scenario GW1.0. New or NZE MURB will need additional measures to combine with natural ventilation to eliminate the risk of overheating in future GW scenarios.

GW may reduce heating energy by up to 21% and increase cooling energy by up to 48% in new or NZE MURB.

Figure 75 shows the effect of global warming degree on the relative (with respect to GW0.0) changes in the heating, cooling and total (heating + cooling) energy use of retrofitted, new (current) and NZE MURBs. As expected, global warming decreases the heating and total energy use but increases the cooling energy use. By the end of the 21st century, the relative changes in the energy usage of all MURBs would be at least -21% for heating and 48% for cooling.

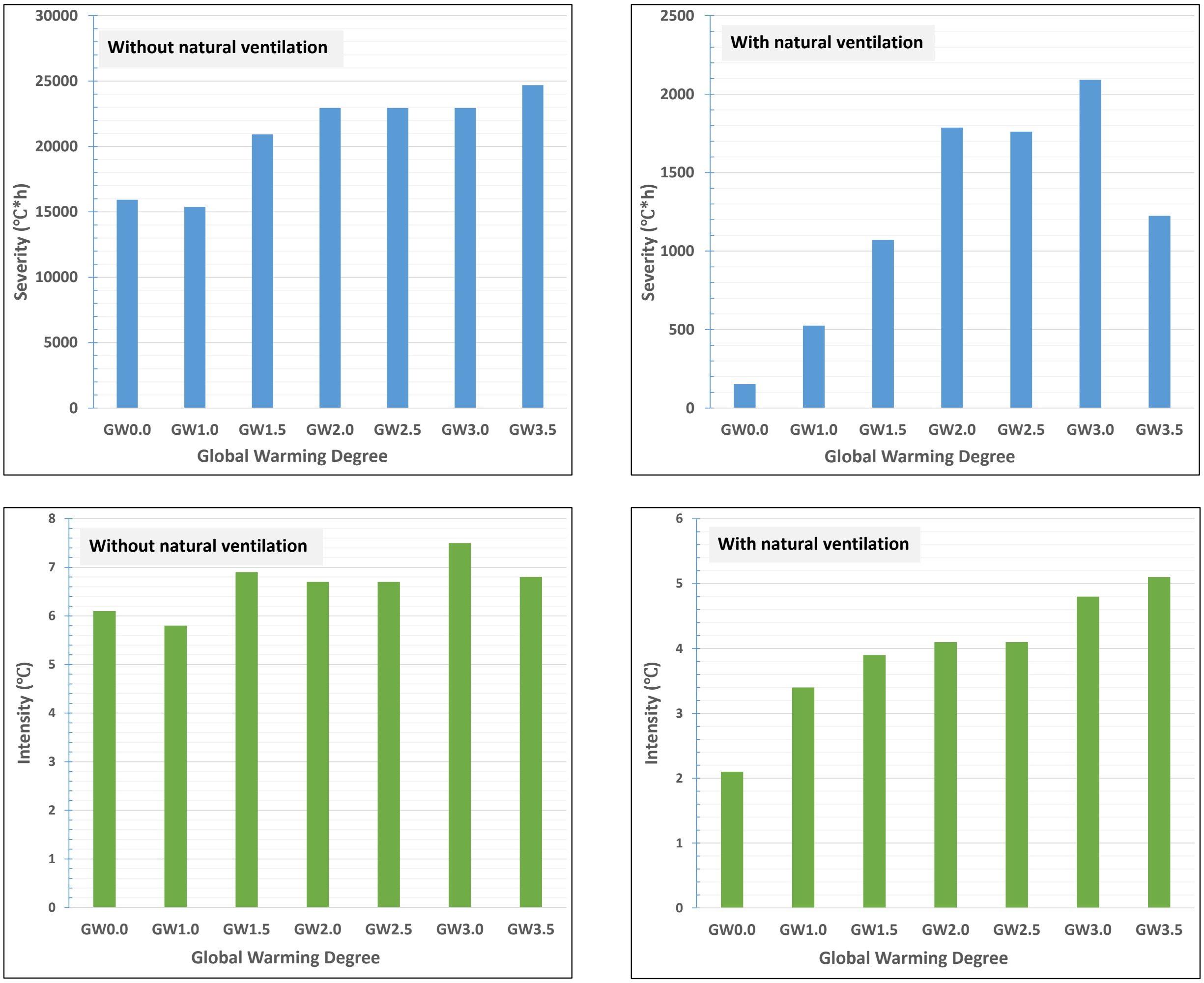


Figure 72: Effects of global warming scenarios on maximum severity and intensity of overheating in suites without or with natural ventilation of retrofitted MURB

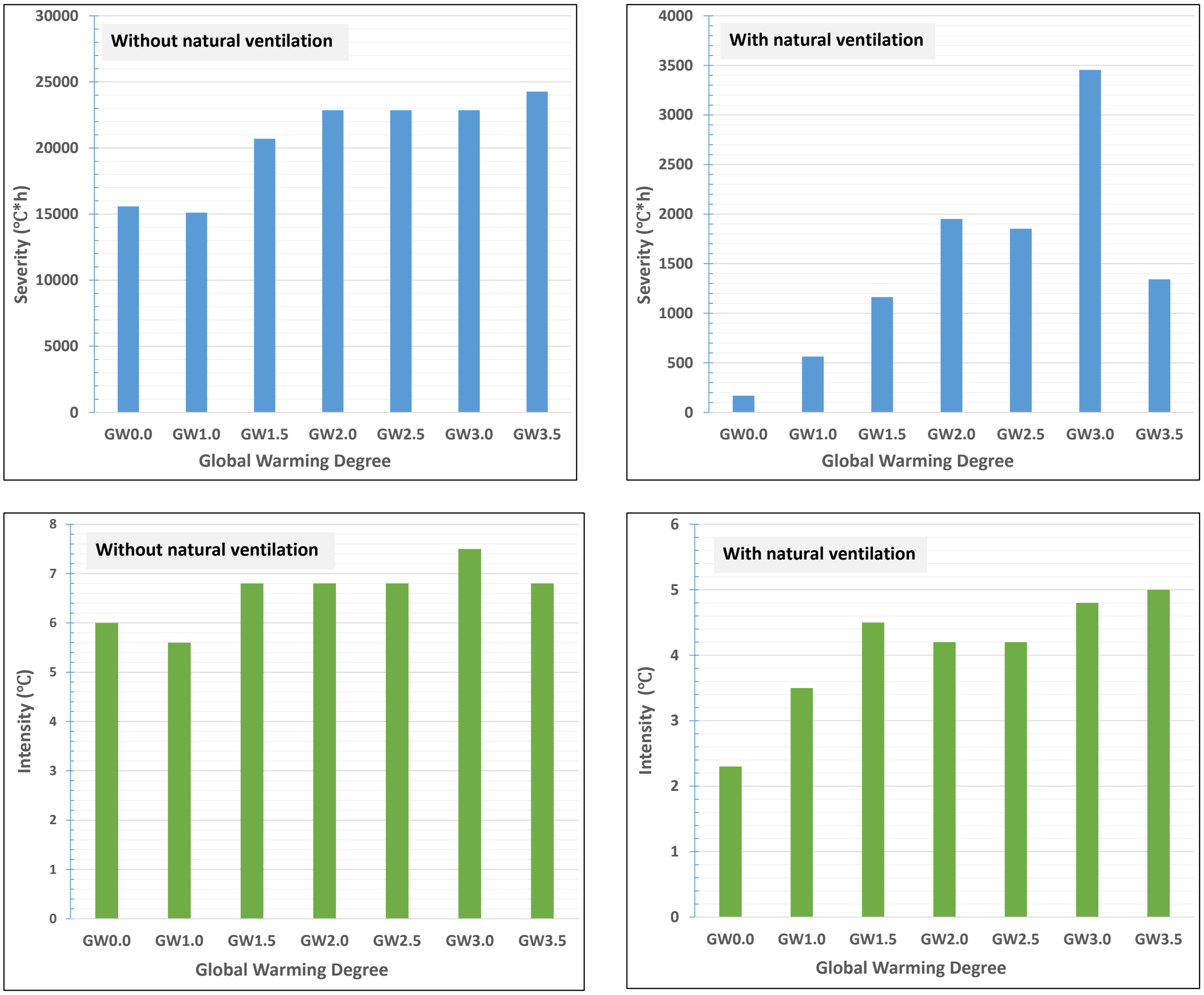


Figure 73: Effects of global warming scenarios on maximum severity and intensity of overheating in suites without or with natural ventilation of current MURB

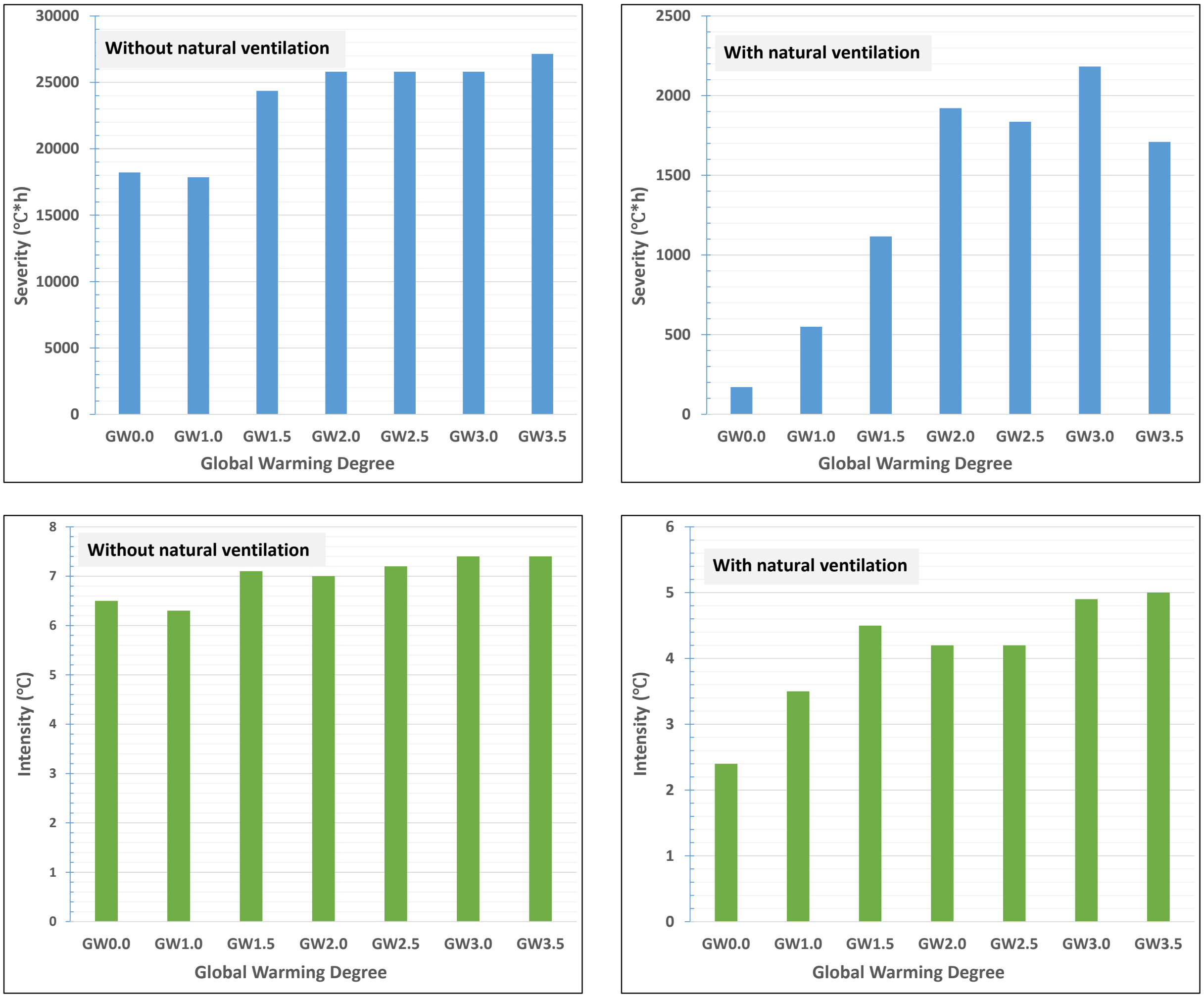


Figure 74: Effects of global warming scenarios on maximum severity and intensity of overheating in suites without or with natural ventilation of NZE MURB

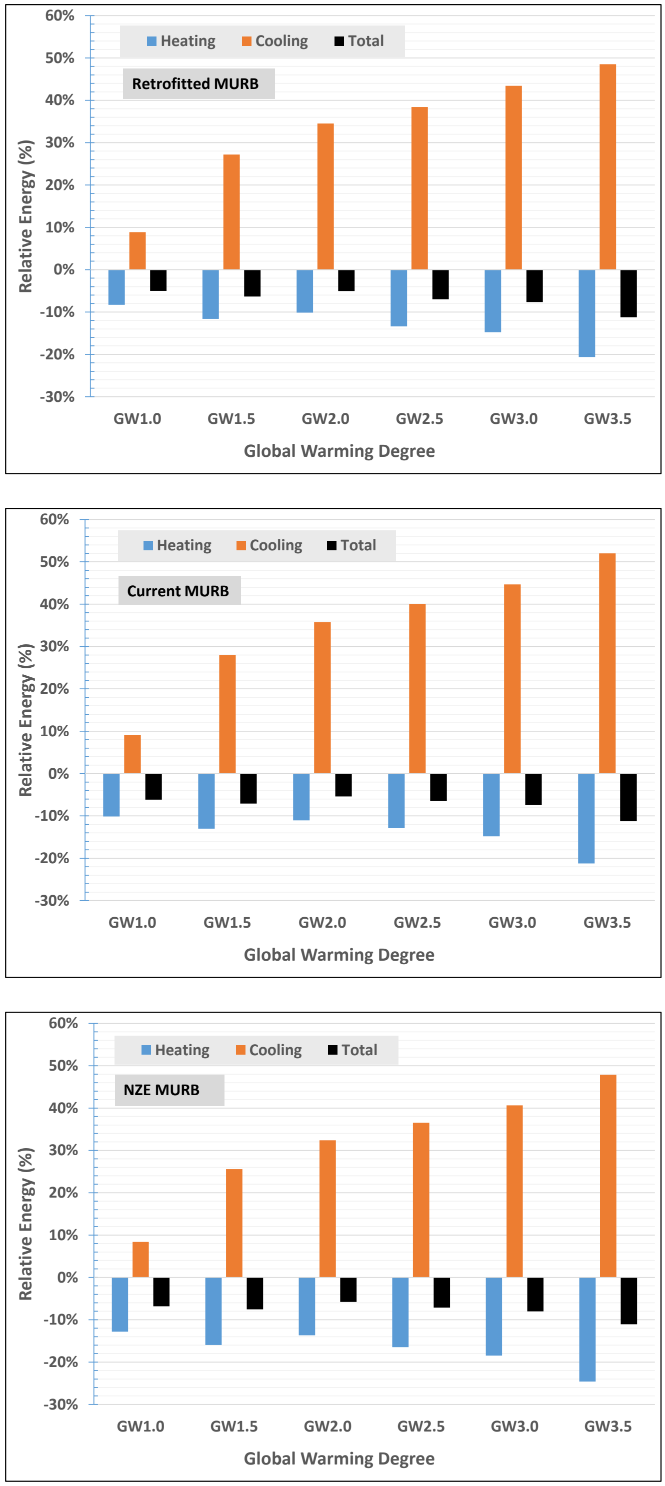


Figure 75: Effects of global warming scenarios on relative changes in MURB energy use for heating, cooling and total (heating + cooling)

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Appendix A - BUILDING SIMULATION MODELS

A.1 Simulation software

EnergyPlus V9.2.0 (https://energyplus.net/)

A.2 Building models

A.2.1 Building archetypes

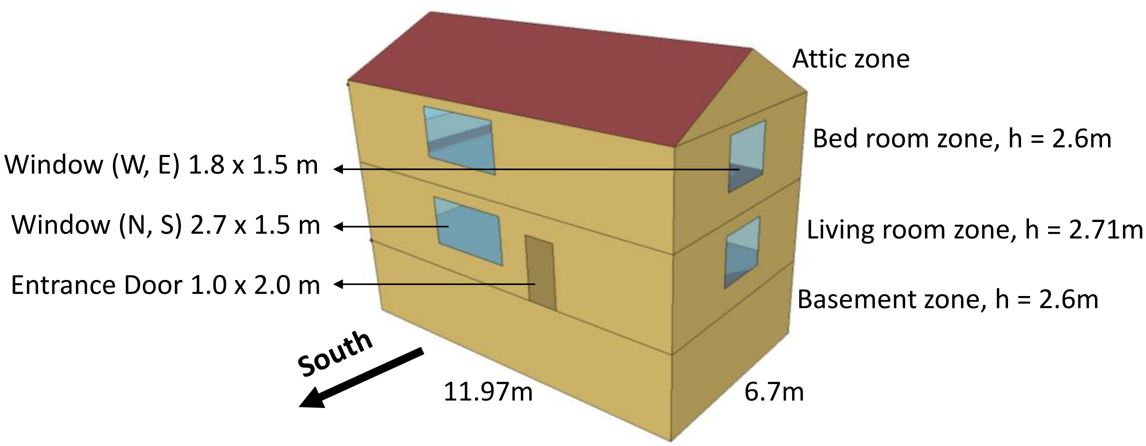


Figure 76. Archetype of a single-detached house model

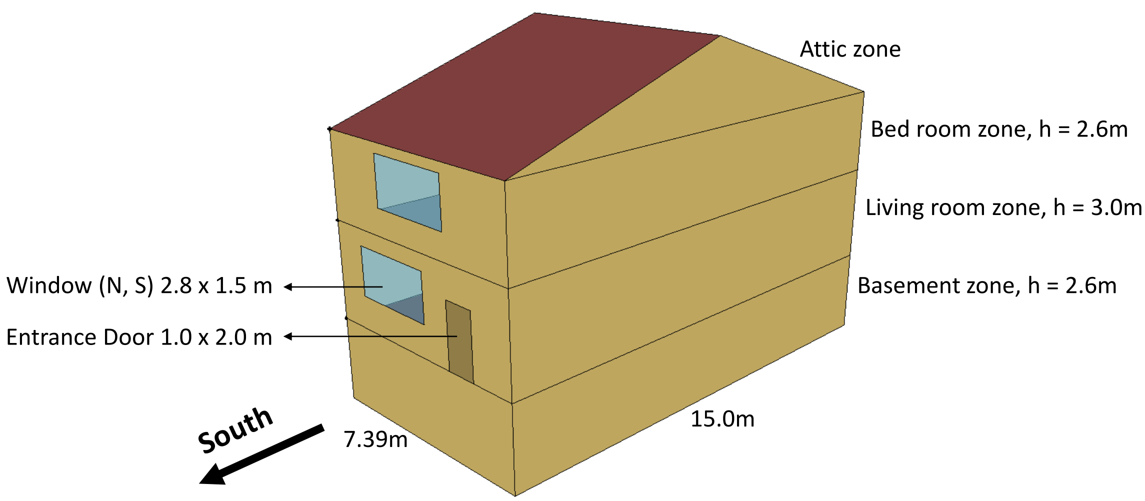


Figure 77. Archetype of a row house model

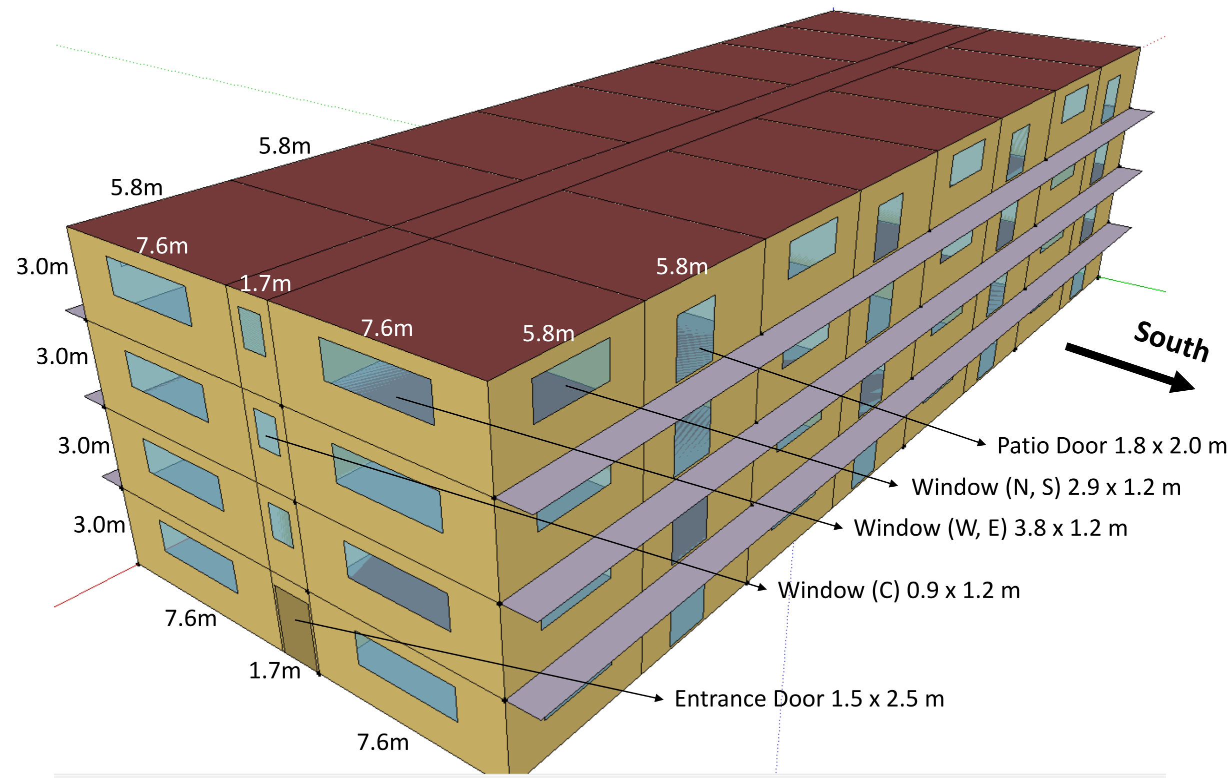


Figure 78. Archetype of a mid-rise MURB model

Figure 79. Plan view of the mid-rise MURB model with thermal zones and names of suite units. Note that suite SE at the first floor is converted to two office spaces

A.2.2 Building model characteristics

Table 13. Building model characteristics

Building →	Detached house	Row house	Mid-rise MURB
Dimensions, m : L*W*H	11.97 x 6.7 x 7.91	7.39 x 15.0 x 8.2	46.4 x 16.9 x 12.0
Windows: WWR	0.16	0.22	0.2
Occupants No.	3	3	3
Equipment heat gain, W/m^2 (NRC, 2015)	5	5	10
Lighting heat gain, W/m^2 (NRC, 2015)	5	5	5.5
Service hot water heat gain, W/person (NRC, 2015)	500	500	500

Table 14. Building air leakage rates

Construction →	Old (1980s) *	Retrofit **	Current (2015)*	NetZero***
Detached house	6.86 ACH	5.34 ACH	2.32 ACH	1.63 ACH
Row house	7.43 ACH	5.7 ACH	2.8 ACH	1.96 ACH
Mid-rise MURB****	4.32 ACH	3.0 ACH	2.4 ACH	1.68 ACH

***** Data taken from measured NRcan's air leakage rate databases of residential buildings

**Using the formula in: Parekh, A, Roux, L, and Gallant, P. Thermal and air leakage characteristics of Canadian housing. Proc. Of the 11. Canadian conference on building science and technology. Banff, AB (Canada), 21-23 Mar 2007

***Assumed 30% reduction of the current (2015) rates

****Data taken from RDH report. 2013. Air leakage control in MURBs. Development of testing and measurement strategies to quantify air leakage in MURBs.

A.2.3 Building HVAC systems

Table 15. HVAC systems for house models

Construction →	Old (1980s)	Retrofit	Current (2015)	NetZero
HVAC Type	Gas furnace Central AC	Gas furnace, HRV Central AC	Gas furnace, HRV, Central AC	Gas furnace, HRV, Central AC
Gas burner efficiency	0.8	0.95	0.95	0.95
Cooling coil efficiency	COP 2.7	COP 3.28	COP 3.28	COP 3.28
Exhaust fan efficiency	0.6	0.7	0.7	0.7
HRV efficiency	N/A	0.6	0.6	0.6

Table 16. HVAC systems for MURB model

Construction →	Old (1980s)	Retrofit	Current (2015)	NetZero
HVAC Type	Gas central boiler for suites; 100% outdoor air MAU with gas heating coil for corridors; window AC in suites	Gas central boiler for suites; 100% outdoor air MAU with gas heating coil for corridors; window AC in suites	Gas central boiler for suites; HRV in suites; window AC in suites Central MAU for corridors with gas heating coil and electric cooling coil and HRV	Gas central boiler for suites; HRV in suites; window AC in suites Central MAU for corridors with gas heating coil and electric cooling coil and HRV
Gas burner efficiency	0.8	0.95	0.95	0.95
Efficiency of cooling coil of MAU or window AC	COP 2.7	COP 3.28	COP 3.28	COP 3.28
Efficiency of exhaust fans in suites	0.6	0.7	0.7	0.7
HRV efficiency	N/A	N/A	0.6	0.6

A.2.4 Building air flow network

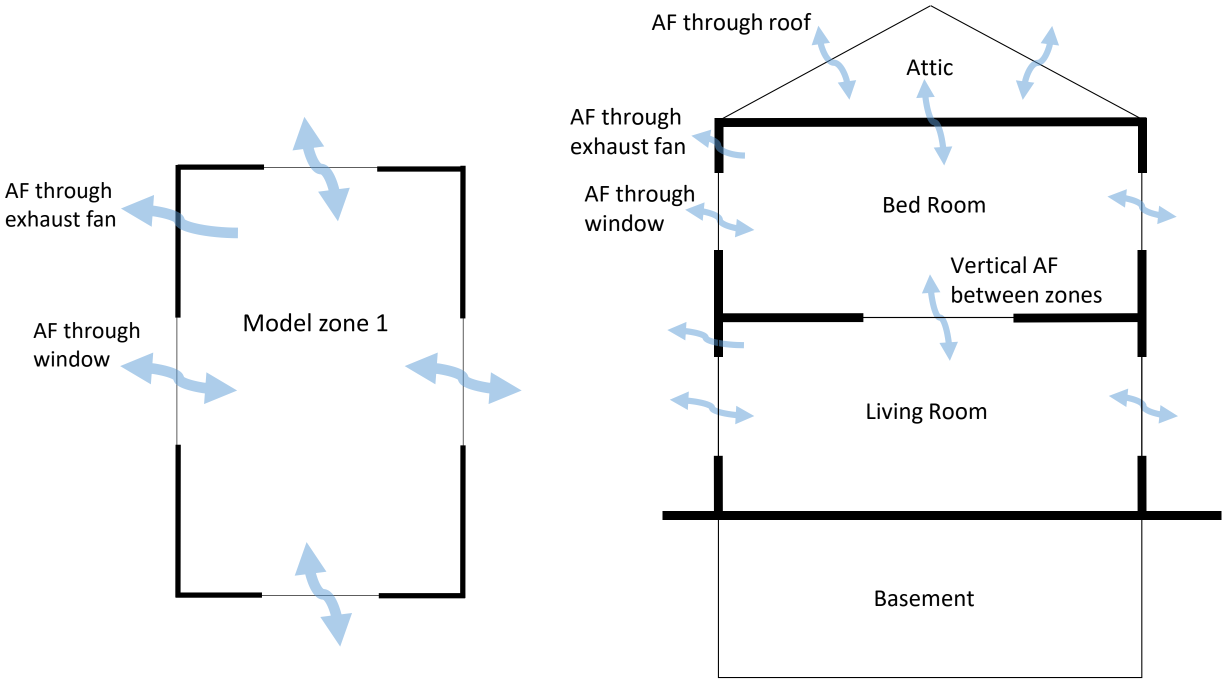


Figure 80. Horizontal and vertical air flow network connections for single detached house model

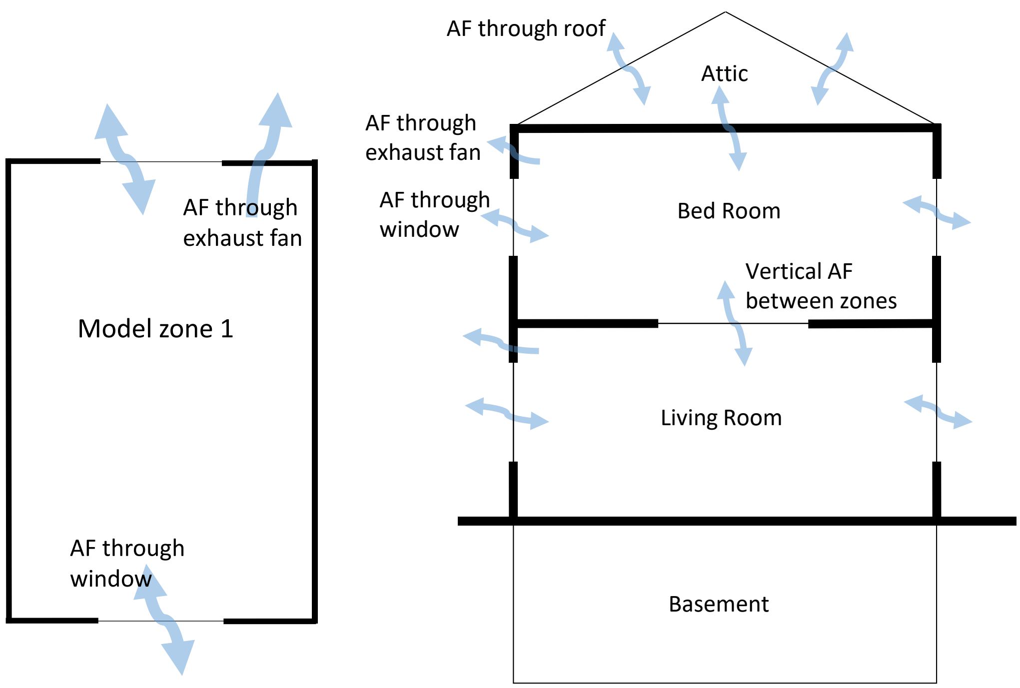
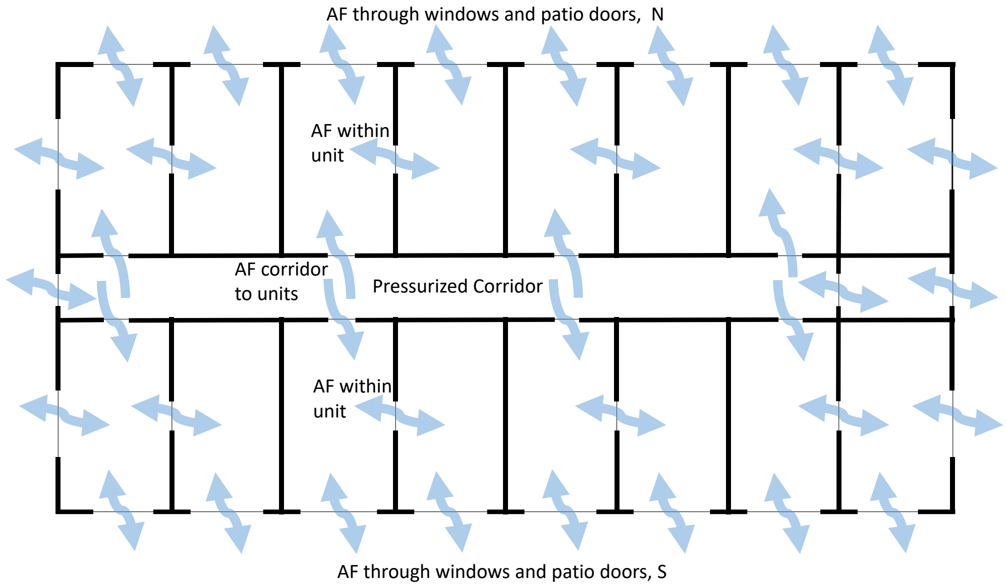


Figure 81. Horizontal and vertical air flow network connections in row house model



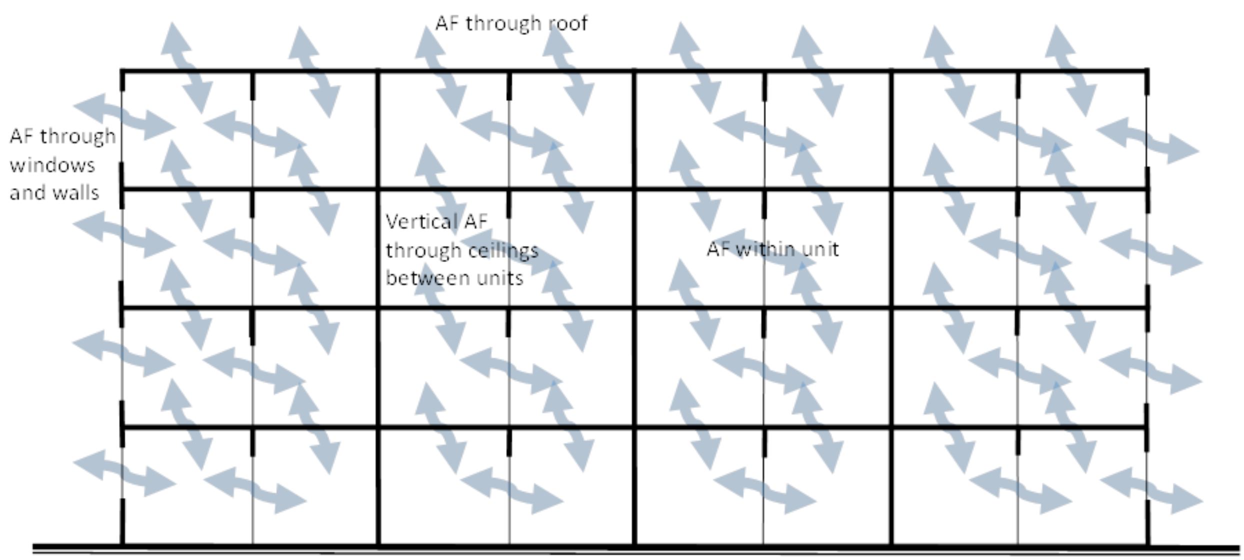


Figure 82. Horizontal and vertical air flow network connections in MURB model

A.3 Calibration of building simulation models

The calibration approach compares the annual energy intensity of buildings as simulated with as published for similar buildings or taken from governmental energy databases of large number of similar buildings in the location under consideration.

Table 17. Calibration of single-detached house model

Energy intensity kWh/m^2	**Model 1980 const.**	**Model 2015 const.**	**CCHT House-old const.***	**CCHT House-R2000 const.***	**NRCan Ontario****	**NRCan Ontario*****
Cooling (electricity)	8.74	9.05	6.8	4.57	5.0	N/A
Heating (gas)	175.28	50.76	142.7	73.38	228.4	108 - 125[xx]
Total	214.22	96.83	N/A	N/A	282	147 - 175[x]

*** Laouadi: Guideline for effective residential solar shading devices, 2010:**
Note. The model includes gas heating, electricity cooling, lightings (no hot water and no appliances)
Old (1980) Construction:
CCHT air leakage value 4.7ACH @50PA; Model (old) 6.86ACH @50Pa
CCHT Wall R value R16; Model (old) R11
CCHT Roof R value R29; Model (old) R20
R2000 construction:
CCHT air leakage value 1.24ACH @50PA; Model (2015) 1.24ACH @50Pa
CCHT Wall R value R25; Model (current) R18
CCHT Roof R value R52; Model (current) R47

** **NRCan 1990, Office of energy efficiency** > Energy use statistics > National energy use database > Comprehensive energy use database > Residential sector; **Table 35**
TOTAL ENERGY IS HEATING, COOLING AND LIGHTING
http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/handbook/tables.cfm
http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/showTable.cfm?type=CP&sector=res&juris=on&rn=35&page=0

*** **NRCan 2011, Survey of household energy use**
[x] Conversion from GJ/m^2 to kWh/m^2. $1GJ/m^2 = 277.778kWh/m^2$;
[xx] Lower number assumed due to some percentage of houses heated by electricity or solid fuels (wood, coal); houses are partially gas heated.

Table 18. Calibration of mid-rise MURB Model

Energy Intensity (kWh/m^2)	Model 1980 const.	Model 2015 const.	NRCan, 2011[1] (2003)	NRCan Ontario[2] 1990 (2016)	TAF, UT[3], 2012	CMHC[4], 2005	OHC, Ontario[5], 2000	NRC, Ontario[6], 1982	HiSTAR[7], 2007
Cooling	11.0	10.5	N/A	1.5 (3.8)	N/A	N/A	N/A	N/A	N/A
Heating (gas)	297.7	167.7	127.8 (N/A)	137.5 (81)	195.6 (67%)	196 (49%)	N/A	N/A	N/A
Electricity	46.6	45.4	55.56 (N/A)	N/A	96.4 (33%)	108 (27%)	N/A	N/A	N/A
Total energy	341.5	210.8	267.08 (305)	190.2 (116.7)	292 (90 - 510)	400 (281 - 581)	232	287 (134 - 672)	275 (136 - 495)

[1] NRCan 2011, Survey of household energy use / Collected average data for households

- **Energy intensity 0.46GJ/m^2 (127.8kWh/m^2)**
- **Electricity intensity 0.2GJ/m^2 (55.56kWh/m^2)**
- **Gas intensity 0.63GJ/m^2 x total number of houses divided by houses that use gas for heating (0.63*5063479/3317817*277.78 = 267.08kWh/m^2)**

[2] NRCan, Office of energy efficiency / Energy use statistics / National energy use database > Comprehensive energy use database > Residential sector; Table 39 **/** TOTAL ENERGY IS HEATING, COOLING AND LIGHTING
http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/handbook/tables.cfm
http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/showTable.cfm?type=CP&sector=res&juris=on&rn=39&page=0

NRCan Energy database for Ontario, 1990

- **Space heating 45.7PJ | 137.5kWh/m^2 / Space cooling 0.5PJ | 1.5kWh/m^2 | Floor space 92.3*10^6 m^2.**
- **Total (heating, cooling, lighting, appliance). 0.94GJ/m^2 | 260.2kWh/m^2**

NRCan Energy database for Ontario, 2016

- **Space heating 44.3PJ | 116.45kWh/m^2 / Space cooling 2.1PJ | 10.0kWh/m^2 | Floor space 151.9*10^6 m^2.**
- **Total (heating, cooling, lighting, appliance). 0.56GJ/m^2 | 155.3kWh/m^2**

[3] University of Toronto, Retrofit Opportunities in MURBs in the City of Toronto, 2012

- Database of existing buildings. Chapter 3.2 Refined data set energy intensity, page 8. (Normalized to CWEC).
- Refs. summarized by: C. Binkley, Energy Consumption trends of Multi-Unit Residential Buildings in the City of Toronto, U. of Toronto, 2012

[4] CMHC, Douglas Hart, Energy and Water Consumption Load Profiles in Multi-Unit Residential Buildings, 2005
[5] CMHC Enermodal Engineering Limited, Review of OHC Building Energy and Water Audits, 2000
[6] NRC, A Hakim Elmahdy, Building Research Note: Annual Consumption Data on Apartment Buildings, 1982
[7] Canadian Bldg. Energy End-Use Data & Analysis Centre, R. Liu, Energy Consumption & Energy Intensity in Multi-Unit Residential Buildings in Canada, 2007

A.4 Ventilation strategies

Table 19. Ventilation strategies for single detached and row house models

Measure	Old	Retrofit	Current	NetZero
Default mechanical ventilation	Continuous kitchen exhaust fan in first floor (12 litre/s) and bathroom fan in second floor (10 litres/s)	HRV (nominal flow rate 35 litre/s) + Exhaust fans	HRV + Exhaust fans	HRV + Exhaust fans
Natural ventilation: Open windows if T_{in} > 26˚C and T_{out}	25% open	25% open	25% open	25% open
Nighttime ventilation	Exhaust fans + 10x fan flow rate between 10:00 PM and 9:00 AM	HRV + Exhaust fans + 10x fan flow rate between 10:00 PM and 9:00 AM	HRV + Exhaust fans + 10x fan flow rate between 10:00 PM and 9:00 AM	HRV + Exhaust fans + 10x fan flow rate between 10:00 PM and 9:00 AM
Mixed mode ventilation	Exhaust fan + Natural ventilation + Nighttime ventilation	HRV + Exhaust fans + Natural ventilation + Nighttime ventilation	HRV + Exhaust fans + Natural ventilation + Nighttime ventilation	HRV + Exhaust fans + Natural ventilation + Nighttime ventilation

Table 20. Ventilation strategies for MURB model

Measure	Old	Retrofit	Current	NetZero
Default mechanical ventilation	Continuous exhaust fans in suites (22 litre/s); 100% outdoor air MAU with pressurised corridor system	Continuous exhaust fans in suites (22 litre/s); 100% outdoor air MAU with pressurised corridor system	Continuous exhaust fans (22 litre/s) and HRV (24 litre/s) in suites; MAU for corridors	Continuous exhaust fans (22 litre/s) and HRV (24 litre/s) in suites; MAU for corridors
Natural ventilation: Open windows if T_{in} > 26˚C and T_{out}	10% bedroom windows; 50% patio door	10% bedroom windows; 50% patio door	10% bedroom windows; 50% patio door	10% bedroom windows; 50% patio door
Nighttime ventilation	Exhaust fans + 10x HRV flow rate (24l/s)) between 10:00 PM and 9:00 AM	Exhaust fans + 10x HRV flow rate between 10:00 PM and 9:00 AM	HRV + Exhaust fans + 10x HRV flow rate between 10:00 PM and 9:00 AM	HRV + Exhaust fans + 10x HRV flow rate between 10:00 PM and 9:00 AM
Mixed mode ventilation	Exhaust fans + Natural ventilation + Nighttime ventilation	Exhaust fans + Natural ventilation + Nighttime ventilation	HRV + Exhaust fans + Natural ventilation + Nighttime ventilation	HRV + Exhaust fans + Natural ventilation + Nighttime ventilation

A.5 Solar shading devices

Table 21. Shading device types for building models

Shading type and description	Controls
Internal horizontal Venetian blinds, reference	Open with horizontal slat angle of 90° in winter Closed with slat angle of 175° in summer (May to Sep.)
Exterior grey screen shading with 5% openness factor	Retracted in winter and fully closed in summer
Internal reflective Venetian blinds with a 70% solar reflectivity	Open with horizontal slat angle of 90° in winter Closed with slat angle of 175° in summer (May to Sep.)
Thermochromic windows, double glazed	Self-controlled between glass temperature of 25°C (clear) and 65°C (fully tinted)
Electrochromic windows, double glazed	Fully tinted if solar radiation incident on window is higher than 150 W/m^2 and T_{out} > 20°C

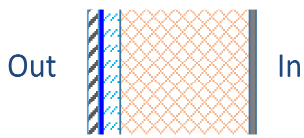
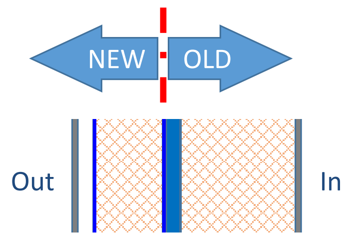
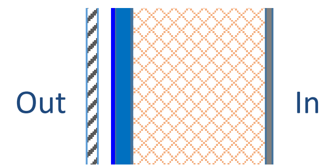
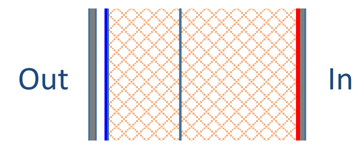
A.6 Windows types

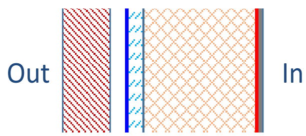
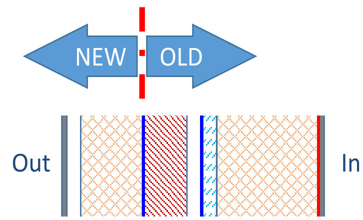
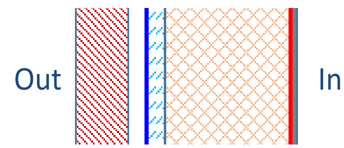
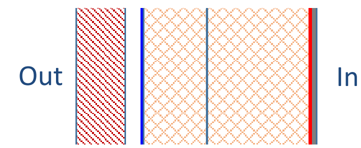
Table 22. Window types (ε is emissivity)

Name	Glazing Unit	Description	Performance Indices (center of glass section)		
			VT	SHGC	U-Factor (W/m^2K)
Dclear	double clear	6 mm Pilkington Optifloat clear 13 mm air 6 mm Pilkington Optifloat clear	0.78	0.702	2.58
Dclear + EL	double clear with low solar heat low-e (ε = 0.042)	6 mm Cardinal 272 Low-e (surf. #2) 13 mm 10% air & 90% argon 6 mm Pilkington Optifloat clear	0.69	0.42	1.33
Dclear + EH	double clear with high solar heat low-e (ε = 0.157)	6 mm Pilkington Optifloat clear 13 mm 10% air & 90% argon 6 mm Pilkington Energy Advantage Low-e (surf. #3)	0.73	0.67	1.58
Dgreen + eL	double green with low solar heat low-e (ε = 0.044)	6 mm Guardian Low-e green (surf. #2) 13 mm 5% air & 95% argon 6 mm Pilkington Optifloat clear	0.56	0.30	1.34
Thermochromic	Thermochromic with low-e (clear @ 25°C & dark @ 65°C states)	6 mm clear glass 1.24 mm Suntuitive interlayer 5 mm clear glass 13 mm 10% air & 90% argon 6 mm Cardinal 272 Low-e (surf. # 3)	0.56	0.414	1.37
			0.08	0.184	1.37
Electrochromic	Electrochromic with low-e coating (Tint 1-clear & Tint 4-dark)	6 mm clear glass / electrochromic coating / surface #2 13 mm 10% air & 90% argon 6 mm Cardinal 272 Low-e (surf. # 3)	0.50	0.345	1.38
			0.026	0.074	1.38
Tclear + eL	Triple clear with low solar heat Low-e (ε_2 = 0.042, ε_5 = 0.042)	6 mm Cardinal Low-e-272 clear 13 mm 5% air & 95% argon 6 mm Pilkington Optifloat clear 13 mm 5% air & 95% argon 6 mm Cardinal Low-e-272 clear	0.54	0.35	0.57
Tclear + EH	Triple clear with high solar heat Low-e (ε_3 = 0.157, ε_5 = 0.157)	6 mm Pilkington Optifloat clear 13 mm 5% air & 95% argon 6 mm Pilkington Energy Advantage Low-e 13 mm 5% air & 95% argon 6 mm Pilkington Energy Advantage Low-e	0.60	0.57	0.78

A.7 Wall constructions of house models

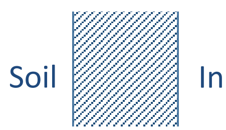
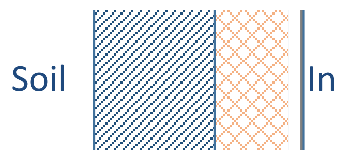
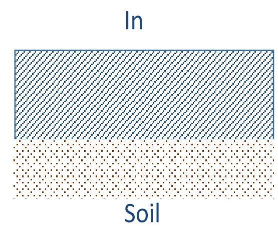
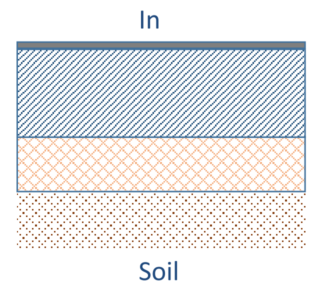
Table 23. Wall assemblies types for detached and row house models

Construction type		Old (1980s)	Retrofit	Current (NBC 2015)	Future NZE assembly
Light	**Geometry**				
	Assembly	• Wood siding 19mm • Weather resistant barrier • Fiberboard sheathing 19mm • Wood stud (2x4") 100mm with batt insulation • Vapor Control, poly sheet • Drywall 12mm	• Vinyl siding/Fiber reinforced concrete panels 15mm • Air cavity 25mm • Weather resistant barrier • Mineral wool insulation 100mm • Existing Structure (left column) with exterior siding and furring strips removed	• Profiled Vinyl siding 15mm • Air cavity 25mm • Weather resistant barrier • EPS (C. I.) 25mm • Wood stud (2x6") 150mm with batt insulation • Vapor Control, poly sheet • Drywall 12mm	• Vinyl siding 15mm • Weather resistant barrier • Mineral wool Insulation 100mm • OSB sheathing 12mm • Wood stud (2x6") 150mm with batt insulation • Vapor Control, poly sheet • Drywall 12mm
	Effective R: m^2K/W $(ft^2 \cdot °F \cdot h/BTU)$	R1.8 (R10)	R4.2 (R24)	R3.2 (R18)	R4.6 (R26)

Construction type		Old (1980s)	Retrofit	Current (NBC 2015)	Future NZE assembly
Medium	**Geometry**				
	Assembly	• Clay brick veneer 100mm • Air cavity 25mm • Weather resistant barrier • Gypsum sheathing 12mm • Wood stud / 150mm with batt insulation • Vapor Control, poly sheet • Drywall 12mm	• Fiber reinforced concrete panels 15mm • Air Cavity 25mm • Mineral wool insulation 100mm • Vapor permeable coating • Existing Structure (left column)	• Clay brick veneer 100mm • Air cavity 25mm • Weather resistant barrier • EPS (C. I.) 25mm • Wood stud / 150mm with batt insulation • Vapor Control, poly sheet • Drywall 12mm	• Clay brick veneer / 100mm • Air cavity / 25mm • Weather resistant barrier • Mineral wool Insulation 100mm • OSB sheathing / 12mm • Wood stud / 150mm with batt insulation • Vapor Control, poly sheet • Drywall / 12mm
	Effective R: m^2K/W ($ft^2 \cdot °F \cdot h/BTU$)	R2.6 (R15)	R5.0 (R28)	R3.2 (R18)	R4.8 (R27)

A.8 Basement walls and slabs of house models

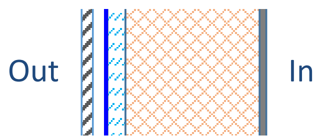
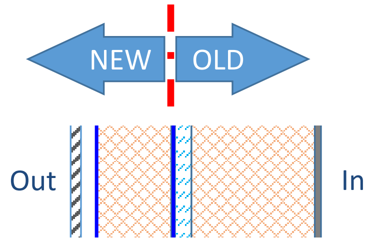
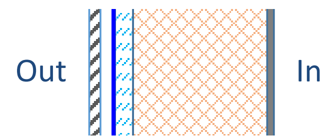
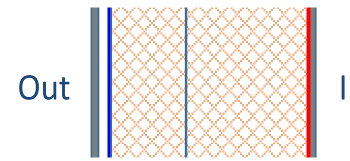
Table 24. Basement wall and slab constructions of house models

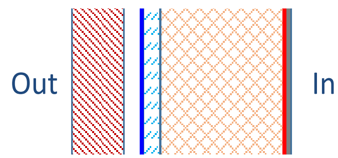
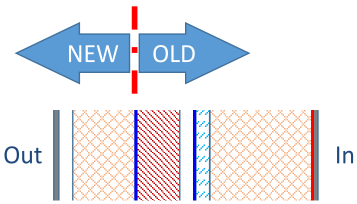
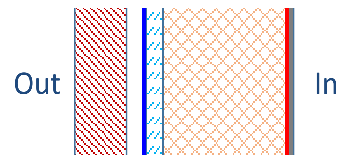
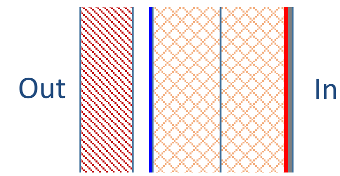
Basement construction	**Wall**		**Slab**	
	Uninsulated	Insulated	Uninsulated	Insulated
Geometry				
Assembly	• 150mm Concrete	• 150mm Concrete • 50mm Batt insulation • Vapor Control, poly sheet	• 150 mm Concrete • 100 mm Coarse granular fill	• 20mm Flooring • 150mm Concrete • 50mm XPS • 100mm Course granular fill
R: m^2K/W ($ft^2 \cdot °F \cdot h/BTU$)	R0.5 (R3)	R1.7 (R9)	R0.6 (R3)	R1.6 (R9)

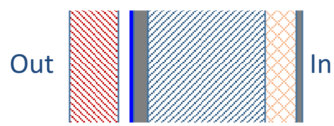
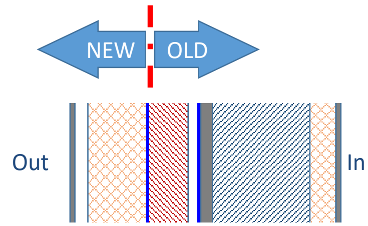
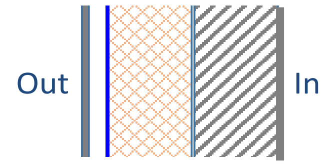
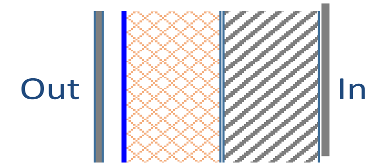
Reference: CCBFC: National Building Code of Canada, 2015

A.9 Wall constructions of MURB model

Table 25. Wall assembly types for MURB model

Construction type		Old (1980s)	Retrofit	Current (NBC 2015)	Future NZE assembly
Light	Geometry				
	Assembly	• Wood cladding 20mm • Air cavity 25mm • Weather resistant barrier • Gypsum sheathing 12mm • Steel stud 150mm with batt insulation • Vapor Control, poly sheet • Drywall 12mm	• Fiber reinforced concrete panels 15mm • Air cavity 25mm • Weather resistant barrier • Mineral wool insulation 100mm • Existing Structure (left column) with exterior siding and furring strips removed	• Fiber reinforced concrete panels 15mm • Air cavity 25mm • Weather resistant barrier • EPS (C. I.) 25mm • Steel stud 150mm with batt insulation • Vapor Control, poly sheet • Drywall 12mm	• Fiber reinforced concrete panels 15mm • Air cavity 25mm • Weather resistant barrier • Mineral wool Insulation 100mm • OSB sheathing 12mm • Steel stud 150m with batt insulation • Vapor Control, poly-sheet • Drywall 12mm
	Effective R: m^2K/W ($ft^2 \cdot °F \cdot h/BTU$)	R1.7 (R10)	R3.8 (R22)	R2.2 (R12)	R3.8 (R22)

Construction type		Old (1980s)	Retrofit	Current (NBC 2015)	Future NZE assembly
Medium	Geometry				
	Assembly	• Clay brick veneer 100mm • Air cavity 25mm • Weather resistant barrier • Gypsum sheathing 12mm • Steel stud 150mm - with batt insulation • Vapor Control, poly sheet • Drywall 12mm	• Fiber reinforced concrete panels 15mm • Air Cavity 25mm • Mineral wool insulation 100mm • Vapor permeable coating • Existing Structure (left column)	• Clay brick veneer 100mm • Air cavity 25mm • Weather resistant barrier • EPS (C. I.) 50mm • Steel stud 150mm - with batt insulation • Vapor Control, poly sheet • Drywall 12mm	• Clay brick veneer 100mm • Air cavity 25mm • Weather resistant barrier • Mineral wool insulation 100mm Steel stud 150mm - with batt insulation • Vapor Control, poly sheet • Drywall 12mm
	Effective R: m^2K/W (ft^2·°F·h/BTU)	R1.7 (R9)	R4.1 (R23)	R3.1 (R18)	R3.9 (R22)

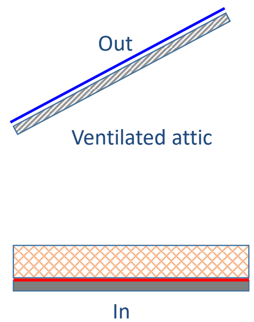
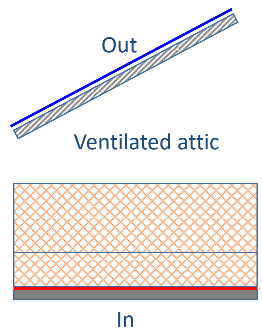
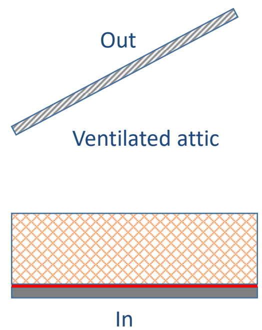
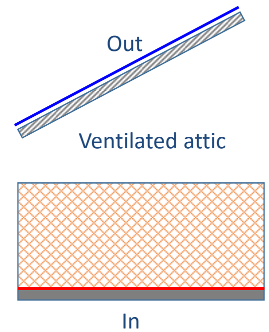
Construction type		Old (1980s)	Retrofit	Current (NBC 2015)	Future NZE assembly
Heavy	Geometry				
	Assembly	• Clay brick veneer 100mm • Air cavity 25mm • Weather resistant barrier • Insulation board / 25mm • CMU / 150mm • Interior insulation 25mm • Drywall 12mm	• Fiber reinforced concrete panels 15mm • Air Cavity 25mm • Mineral wool insulation 100mm • Vapor permeable coating • Existing Structure (left column)	• Fiber reinforced concrete panels 15mm • Air Cavity 25mm • Water resistant barrier • Mineral wool insulation 120mm • Concrete wall / 150mm • Drywall / 12mm	• Fiber reinforced concrete panels / 15mm • Air Cavity 25mm • Weather resistant barrier • Mineral wool insulation 150mm • Concrete wall / 150mm • Drywall 12mm
	Effective R: m^2K/W ($ft^2·°F·h/BTU$)	R1.6 (R9)	R4.0 (R23)	R3.0 (R17)	R3.7 (R21)

References:

1) Wall assembly layers taken from:
   1980s CMHC: Canadian Wood-Frame House Construction, 1988
   Current: CMHC: Canadian Wood-Frame House Construction, 2013
   CCBFC*: National Building Code of Canada, 2015
   Retrofits: RDH: Deep Building Enclosure Energy Retrofit Study, 2017
   * Canadian Commission on Building and Fire Codes
2) R effective: ASHRAE, Handbook of Fundamentals, 2017, (with incorporated effect of wood studs thermal bridging). Appendix B1

A.10 Roofs constructions of house models

Table 26. Roof constructions of house models

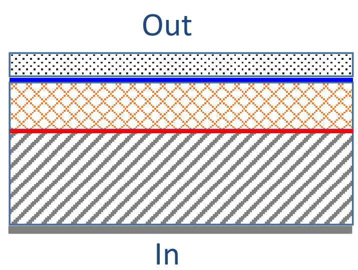
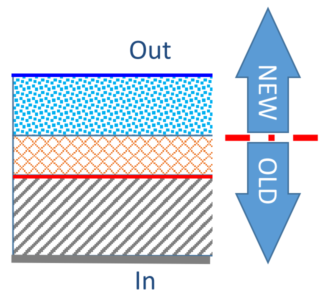
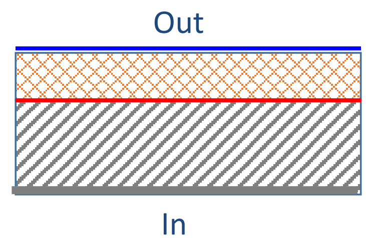
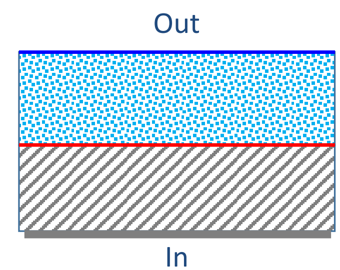
<table>
<tr><th>Const.</th><th>1980s</th><th>Retrofit</th><th>Current (NBC 2015)</th><th>Future NZE assembly</th></tr>
<tr><td>Geometry</td>
<td></td>
<td></td>
<td></td>
<td></td></tr>
<tr><td>Assembly</td>
<td>• Asphalt shingles 5mm
• Membrane underlayment
• OSB sheathing 12mm
• Attic air cavity
• Blown insulation 150mm
• Vapor Control, poly sheet
• Drywall 12mm</td>
<td>• Asphalt shingles 5mm
• Membrane underlayment
• OSB sheathing 12mm
• Attic air cavity
• Added Blown insulation 200mm
• Original Blown insulation 150mm
• Vapor Control, poly sheet
• Drywall 12mm</td>
<td>• Asphalt shingles 5mm
• Membrane underlayment
• OSB sheathing 12mm
• Attic air cavity
• Blown insulation 350mm
• Vapor Control, poly sheet
• Drywall 12mm</td>
<td>• Asphalt shingles 5mm
• Membrane underlayment
• OSB sheathing 12mm
• Attic air cavity
• Blown insulation 500mm
• Vapor Control, poly sheet
• Drywall 12mm</td></tr>
<tr><td>R: m^2K/W ($ft^2 \cdot °F \cdot h/BTU$)</td><td>R3.6
(R20)</td><td>R8.2
(R47)</td><td>R8.2
(R47)</td><td>R11.7
R66</td></tr>
</table>

References:

CMHC: Canadian Wood-Frame House Construction, 1988
CMHC: Canadian Wood-Frame House Construction, 2013
CCBFC: National Building Code of Canada, 2015

A.11 Roof constructions of MURB model

Table 27. Roof constructions of MURB model

Const.	1980s	Retrofit	Current (NBC 2015)	Future HP assembly
Geometry				
Assembly	• Gravel 50mm • Asphalt membrane 10mm • Board ISO insulation 50mm • Vapor Control, poly sheet • Substrate, concrete 150mm • Plaster 10mm	• Reflective/non-reflective membrane 1.5mm • Board XPS insulation 100mm • Existing Structure (left column) with gravel and asphalt removed	• Reflective/non-reflective membrane 1.5mm • Board ISO insulation 125mm • Vapor Control, poly sheet • Substrate, concrete 150mm • Plaster 10mm	• Membrane 1.5mm • Board XPS insulation 250mm • Vapor Control, poly sheet • Substrate, concrete 50mm • Plaster 10mm
R: m^2K/W ($ft^2 \cdot °F \cdot h/BTU$)	R2.6 (R15)	R5.4 (R30)	R6.1 (R34)	R7.3 (R41)