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Climate Resilience of Buildings: Overheating in Buildings — Literature Review

A. Laouadi, A. Gaur, and M. Bartko

Report: CRBCPI-Y2-R14

15-June-2018



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Climate Resilience of Buildings: Overheating in Buildings — Literature Review

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Executive Summary

Under the Pan-Canadian Climate Change Framework, Infrastructure Canada has provided funding to NRC to deliver the Climate-Resilient Buildings and Core Public Infrastructure (CRBCPI) Project over a five year period. The purpose of the project is to develop decision support tools, including codes, guides and models for the design of new climate resilient buildings (CRB) and core public infrastructure (CPI) and rehabilitation of existing buildings and CPI in key sectors to ensure that the impact of existing and future climate change and extreme weather events are addressed.

This report relates to the research project **A1-012820-06: Overheating in Buildings** under the CRBCPI Project. The specific goal of project **A1-012820-06** is to develop guidelines to address the overheating risk in retrofitted and new buildings as may arise from climate change and extreme heat events. The guidelines are also intended to feed the future updates of the National Building Code of Canada on the climate resilient design of buildings.

The report presents a state of the art literature review on the effects of climate change and extreme heat events on the overheating risk of building interior spaces and its consequences on the heat-related health of building occupants. More than 270 technical articles and best practice guides have been reviewed. The review is summarized as below:

It is unequivocal that the climate has been warming over the past decades and is projected to worsen in the future. Overheating of building interior spaces as may arise from such global warming and extreme heat events has been identified as a major concern to the comfort and health of vulnerable people, overloading of building HVAC systems, increasing the cost and burden of the health care system, and straining of the electric and water utility demands.

Prolonged exposure to extreme heat induces heat stresses on the health of people that may lead to severe health issues (such as cramps, heat exhaustion and fatal heat stroke) or even death. Furthermore, extreme heat events increase environmental chemical reactions that can lead to issues of indoor air quality, which in turn pose a greater risk to the human health. Extreme heat events in urban heat island city centers combined with air pollution in industrial areas were found to increase morbidity (sickness), mortality (loss of life), food and energy prices, and insurance claims, particularly in North America. The extent of this effect varies from climate to climate, region to region, and city to city. In Canada and the USA, the number of excess mortalities due to extreme heat events is higher than any other natural hazard event such as storms and floods. Heat-related mortality is largely preventable if proper actions and adaptation measures are implemented at a community and/or individual level to reduce the risk of extreme heat events. In this regard, many Canadian jurisdictions from the east to the west coasts have developed various extreme heat adaptation measures through the establishment of extreme heat alert systems and response plans, particularly at a community level. Canadian health organisations have also developed best practice guidebooks and guidelines to assess the vulnerability and adaptation of health care workers to extreme heat events. Studies on climate change adaptations at

a building (or individual) level have been, however, very limited in the Canadian context due to the lack of information on exposure to elevated indoor temperatures.

Effect of heat on the human health

The effect of heat on the human health is a well-known topic in the medical discipline as it directly leads to illnesses and tissue injury or damage. Heat-related illnesses and injuries develop when the body core temperature is higher than 37°C, resulting in heat cramps, heat exhaustion or fatal heat stroke.

Vulnerable people such as seniors, sick people and children are the most affected by heat due to limitations of their thermo-regulatory systems.

Climate change effects

The review included various modeling approaches to predict future climate change and extreme heat events and generate the required hourly weather data for building thermal simulation. Changes in climate can occur both due to natural factors and anthropogenic (human-made) factors. The World Meteorological Organisation has recommended a 30 year time-period as the minimum to smooth out short-term climate variability, and identify robust climate change signals. When analyzing the extreme climatic events, changes in their frequencies, durations, and intensities over the 30 year period are analyzed. Premier climate modelling agencies have generated future projections of climate using Global Climate Models (GCMs) as discussed in details in successive Inter-governmental Panel on Climate Change (IPCC) reports. The GCMs simulate the response of global climate system to greenhouse gas (GHG) emissions following four representative concentration pathways: RCP2.6 scenario that depicts aggressive future climate mitigation; two intermediate scenarios RCP4.5 and RCP6.0; and a business-as-usual RCP8.5 scenario. As such, GCMs are able to simulate global temperatures and temperature extremes with more accuracy than other more heterogeneous variables such as precipitation and wind. Regional climate downscaling techniques are used to produce higher spatial resolution (< 50 km) regional climatic data for performing regional scale impact assessments.

Observational records show that average temperatures across Canada have increased on average by 1.3 °C over the past 50 years, approximately twice the global average. The degree of warming has been found to vary spatially, temporally, and for different climate indices. Stronger increases have been recorded for the daily minimum temperatures than for the 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. The long-term temperature forecasts made by the IPCC models suggest a mean warming of approximately 2 °C to 6 °C in the average temperatures across Canada for the different emission pathway scenarios. The projected changes vary spatially over Canada with some provinces having higher warming magnitudes than the others. The provinces of Nunavut, Northwest Territories, and Manitoba are consistently projected with significantly higher warming than the rest of the Canada. The provinces of Saskatchewan and Yukon Territory also fall marginally above the Canadian average.

Extreme heat events (EHE)

The review included the various definitions of extreme heat events, studies on EHE historical occurrences around the world, and EHE health impact studies on the mortality and morbidity of the population. There is currently no specific definition of EHE which is accepted worldwide. The challenge resides particularly in the selection criteria for threshold values for the intensity and duration of the EHE. The Canadian heat alert system uses a combination of humidex, and the daily maximum and minimum temperatures for a few climatic locations distributed across each province. The EHE-related health outcomes include mortality and morbidity. Although mortality has been well studied, mortality studies have many confounding factors (e.g. air pollution, population socioeconomic status), and the outdoor temperature is typically used as the predictor for excess mortality, which is different than the indoor temperature to which most people (up to 90%) are exposed when present in residences, schools, or workplaces. Morbidity studies have been, however, very limited due to the lack of publicly available data.

Risk factors for EHE-related health of people

The possible risk factors were summarized for the heat related health including vulnerable people, environmental factors, community factors, and factors relating to the built environment.

Heat stress related metrics

The various thermal comfort and heat stress indices developed in the past were summarized in this section. The indices included thermal comfort metrics, physiological heat stress metrics, empirical (or biometeorological) metrics and epidemiological metrics. There are more than 100 metrics, but a few of them are universally used in buildings (e.g., thermal comfort) and occupational heat and safety guides and standards. All metrics are developed for healthy adult people, and there is none that address vulnerable people such as seniors, sick people and children.

Overheating studies

Buildings may play a major role to limit the risk of overheating and thereby protect occupants from the harmful outside environment. Buildings influence the indoor thermal conditions to which people (occupants) are exposed most of the time and to which they experience thermal stress. The indoor conditions are a direct consequence of the outdoor conditions, but the severity of indoor conditions depends on many other factors, amongst which are building type (houses, apartment buildings, schools, hospitals, etc.), internal space usage (occupancy density, internal heat gains), construction characteristics (insulation levels, window surface proportions, orientation of facades), and building operation (air-conditioning use, natural ventilation). Various field measurement and simulation studies on the effects of climate change on overheating in different types of buildings and proper adaptations strategies were reviewed. The review also included studies on how various international organisations have responded to limit the risk of overheating through the development of standards and technical guides for best practice. Various definitions of overheating were presented and analysed to develop a suitable definition for the Canadian context.

Climate Resilience of Buildings: Overheating in Buildings — Literature Review

Authored by

A. Laouadi, Ph.D.; A. Gaur, Ph.D.; and M. Bartko, Ph.D.

1. INTRODUCTION

It is unequivocal that the global climate has been warming consistently over the past few decades. A global average temperature increase of 0.85°C was observed from the historical climate data for the past 130 years (IPCC, 2014). Locally, the temperature warming increase was more than double for the whole Canada and triple for the northern arctic latitudes (ECCC, 2016). The climate change has also been found to be associated with more frequent, longer and intense extreme events such as heat waves and droughts. At the global scale, an increase of the hot temperature extremes in summer and decrease of cold temperature extremes in winter were observed since 1950.

Human influences, driven by the global economic and population growth with its consequences on increasing greenhouse gas emission, have been found to be an extremely likely cause of climate change (IPCC, 2014). As human influences continue to grow, future climate warming is expected to follow. Depending on the greenhouse gas emission scenario, the global climate warming for the late 21st century is projected to likely exceed 1.5°C relative to 1850-1900 (IPCC, 2014). In Canada, the future temperature projection shows significant variability among provinces and territories with an average value exceeding the global value by more than 50% (ECCC, 2016).

Beside global temperature increases, the future climate change is likely to increase the intensity, duration and frequency of extreme heat events. Extreme heat events are characterised by temperatures that are much warmer than the seasonal average.

The future climate change is expected to have a significant impact on building infrastructures and communities and population health (Boyle et al., 2013; IPCC, 2014). Overheating of the built environment as may arise from the global climate warming and extreme heat events has been identified as a major concern to (IOM, 2011; CIBSE, 2014):

1. Affect the comfort and health of particularly vulnerable occupants. Vulnerable occupants include those whose age or prior health status renders them more susceptible to environmental heat stress, and those having reduced economic mobility and capacity to adapt to or mitigate the effects of increasing heat;
2. Reduce the productivity and performance of building occupants;
3. Overload the HVAC systems of buildings leading to potential system operation failure; and
4. Strain the demands of electric and water utilities leading to power outages.

Overheating of the built environment is characterised by indoor temperatures reaching excessive values over a period of time that can lead to negative effects on the comfort and health of building occupants.

Prolonged exposure to extreme heat induces heat stresses on the health of people that may lead to severe health issues (such as heat exhaustion and heat stroke) and in some instances death. As well, increases in environmental chemical reactions attributable to excessive heat may lead to increases in indoor air quality issues that in turn pose a greater risk to health. Extreme heat events in city centers where there is an evident urban heat island effect combined with air pollution in industrial areas was found to increase morbidity (sickness), mortality (loss of life), food and energy prices, and insurance claims, particularly in North America (IPCC, 2014). The extent of this effect varies from climate to climate, region to region, and city to city. In Canada and the USA, the number of excess mortalities due to extreme heat events is higher than any other natural hazard event such as storms and floods (Berko et al, 2014; CDC, 2017; ICLR, 2018).

Heat-related mortality is largely preventable if proper action and adaptation measures are implemented at the community and individual level to reduce the risk of extreme heat events (Vaidyanathan et al., 2017). Heat-related mortality occurs over a few days to a few weeks after the occurrence of the extreme heat event (Gasparrini and Armstrong, 2010), and therefore to avoid any potential loss of life any intervention should be planned ahead of time and responded to promptly. In this regard, many Canadian municipalities from the east to the west coasts have developed various extreme heat adaption measures through the establishment of extreme heat alert systems and response plans, particularly at a community level (Richardson, 2010; Gower et al., 2011; TPH, 2017; Mehiriz and Gosselin, 2016). Canadian health organisations have also developed best practice guidebooks and guidelines to assess vulnerability and adaptation of health care workers to extreme heat events (HC, 2011a, b; 2012). Although relatively well addressed at a community level, studies on climate change adaptations at a building (or individual) level are very limited in the Canadian context. This is a part due to the lack of information on the indoor temperature exposure for both the historical and projected climate data. Furthermore, although there are numerous research studies that have addressed the effects of climate change on overheating in buildings as occurs in various climates around the world, only a few countries have developed standard guides for buildings (CIBSE, 2005).

Buildings that shelter and protect people from the outdoor environment may pose an increased risk to the heat-related health of occupants in various ways. First, building occupants are more exposed to the indoor conditions than the outdoor environment as they spend more than 90% of their time indoors whether in residences, in schools, or in workplaces (IOM, 2011). Depending on the building type, indoor temperatures may exceed the outdoor temperatures by several degrees, particularly for naturally ventilated buildings (TPH, 2015; Touchie et al., 2016; van Loenhout et al., 2016). Second, given the fact that buildings are designed for cold climates in Canada, cooling and ventilation in summer are not mandated in building energy codes and regulations. Many building types (e.g., multi-unit residential

buildings; schools) do not use mechanical cooling to reduce the risk of space overheating. In Canada, the use of air conditioning varies among provinces with an average of 58% and 69% for residential and commercial buildings respectively (NRCan, 2011; 2012). Third, old buildings, which make up a significant portion of the building stock, are leakier and not energy efficient and have poor indoor air quality; such buildings often house vulnerable people (e.g. socially deprived), particularly in social housings and apartment buildings. Fourth, new highly insulated buildings, particularly those having high internal heat gains or fully glazed facades may result in periods of space overheating due to unmet air conditioning demands (Mulville and Stravoravdis, 2016). Furthermore, excessive use of air conditioning in buildings would strain the demand for electricity of utilities with potential consequences of power surges and blackouts and that, in turn, would exacerbate the health risk of occupants. Last but not least, most commercial buildings and MURBS are located in large urban areas. The latter may experience the heat island effect (UHI) with 1 to 12°C warmer temperatures particularly at nighttime compared to the surrounding countryside (Gachon et al., 2016). During a heat wave event, warmer nighttime indoor temperatures, particularly if combined with high humidity, may result in sleep privation, and therefore this exacerbates the heat related health effect during hot days (NASEM, 2016).

Adaptation of old and new buildings to become resilient to future climate change has thus become an urgent need. Recently, the National Research Council through funding from Infrastructure Canada under the Pan-Canadian Climate Change Framework has initiated multiple research projects on climate-resilient buildings and core public infrastructure (CRB-CPI). The purpose of the research projects is to develop decision support tools, including codes, guides and models for the design of resilient new buildings and CPI and rehabilitation of existing buildings in key sectors to address future climate change and extreme weather events. With regards buildings, two projects were identified: (1) Overheating in buildings (**A1-012820-06**) and (2) Hygrothermal response and durability of building envelopes (**A1-012820-05**).

This report is the first deliverable of the project **A1-012820-06**. The report reviews state of the art literature that relates to the effect of climate change on the built environment and the potential health effects on building occupants as may arise from a changing climate. The report is structured as follows:

Section 2: About the overheating project (A1-012820-06)

This section provides an overview of the project and provides the context for this first deliverable of the project.

Section 3: Effect of heat on the human health

This section describes the well-known effects of heat on the human health, and lists the potential heat-related illnesses and injuries that may develop when the body core temperature is higher than the neutral value.

Section 4: Climate change effects

This section reviews previous work related to the historical observational records over Canada, and the various modeling approaches used to predict the future climate change and extreme heat events. Methodologies to generate the hourly weather data for a reference extreme year for overheating analysis are also reviewed.

Section 5: Extreme heat events (EHE)

This section reviews in particular extreme heat events of climate change, including their definition, studies on their historical occurrences around the world, and studies on their health impact on the mortality and morbidity of population.

Section 6: Risk factors for EHE-related health of people

This section reviews and lists the possible risk factors of EHE for the health of particularly vulnerable people. The risk factors are grouped into environmental (climate) factors, community factors, and built environment factors.

Section 7: Heat stress related metrics

This section reviews and lists the many variant types of metrics to quantify the effect of EHE on the comfort and health of people (healthy and vulnerable).

Section 8: Overheating studies

This section focuses on buildings as a potential risk factor for the comfort and health of occupants. It starts with the review of previous work (through field measurement and simulation) around the world to assess the overheating risk in the built environment, and how various international organisations have responded to limit the risk of overheating through the development of standards and technical guides for best practice.

2. ABOUT THE OVERHEATING PROJECT

The goal of the project (**A1-012820-05**) is to develop guidelines to address the overheating in retrofitted and new buildings and the heat related health risks of occupants as they may arise from climate change effects. The guidelines will feed the future updates of the National Building Code of Canada. The specific project objectives are:

1. To review literature on the effects of climate change and extreme heat events on the overheating of building indoor spaces under a Canadian context;
2. To evaluate building responses to climate change;
3. To develop and evaluate the effectiveness of selected resilient (adaptation) measures for new and retrofit buildings;
4. To update the Canadian national building codes to address overheating in buildings;
5. To develop guidelines and tools for overheating in buildings and health risk of occupants arising from climate change effects.

The project is composed of five main tasks as follows:

Task 1 – Literature review

Task 2 – Climate change effects (historical and future data)

Task 3 – Building responses to climate change and extreme heat events

Task 4 – Development of guidelines and tools for overheating in buildings

Task 5 – Proposed changes to the national building code (NBC)

3. EFFECT OF HEAT ON THE HUMAN HEALTH

The effect of heat on human health is a well-known topic in the medical discipline as it directly leads to illnesses and tissue injury or damage (HC, 2011a; EPA, 2016; Yeo, 2004; Parsons, 2003). 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 response of the thermoregulatory system to cool the body by balancing the heat gain with the heat loss. If the environmental conditions are not short term (less than a few weeks), the body will be acclimatized (become tolerant) to such conditions and individuals would use various adaptation measures (e.g., wearing light clothing, reduce direct exposure to heat, and other measures) to restore their thermal comfort (HC, 2011b; Deschenes, 2014). 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).

3.1 PHYSIOLOGICAL RESPONSE TO HEAT

The physiological system of the human body continuously generates heat through its metabolism to maintain a body core temperature within a very tight range of 35°C to 41°C around a mean 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 through radiation, convection and evaporation. If the body core temperature is above the neutral value (37°C) the thermoregulatory system uses two mechanisms to cool the body surface: (1) increase of the peripheral blood flow through higher cardiac output (heart blood flow) and vasodilation of the blood vessels in the skin; and; (2) sweat (water and salt) release 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 relative humidity of the local environment and body dehydration. In hot and dry conditions, heat can easily be removed from body by the evaporative cooling through sweat, and the body cooling capacity is limited to the maximum sweat rate of the sweat glands and fluid intake to replace the loss of water from sweating. If 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 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 organs, potentially resulting in heat-related illnesses (HC, 2011a).

3.2 ACCLIMATISATION AND ADAPTATION

Under natural environmental conditions, people adapt to restore thermal comfort if they experience thermal discomfort by using various adaptation means, which can be grouped as physiological (or acclimatization), behavioural, and psychological (Parsons, 2003).

Acclimatisation refers to the physiological adaptation in response to repeated exposures to hot or cold environment over a few weeks duration (HC, 2011a; ISO, 2017), thus increasing the ability of people to become more tolerant to temperatures higher than the neutral conditions (Parsons, 2003).

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 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, 2003). 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, ventilation 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, 2003). 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 role in naturally ventilated buildings where people are more tolerant to heat than in air conditioned buildings (Brager and de Dear, 1998).

3.3 HEAT RELATED ILLNESSES

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

Heat cramps (mild heat stress) — Are caused by the loss of fluids and salts due to sweating. It is accompanied by painful muscle cramps and spasms, and heavy sweating. Drinking 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 surfaces 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, 2011a). Drinking water and cooling the body may relief the symptoms (EPA, 2006).

Heat stroke — Occurs when the thermoregulatory system fails, the body core temperature reaches 40.6°C or higher (extreme hyperthermia), and the skin becomes hot and dry.. It is accompanied by headache, confusion, nausea and dizziness. Heat stroke is a severe medical emergency, and any delay to its cure may be fatal (Yeo, 2004; EPA, 2006). If it occurs, the body needs immediate cooling (e.g., placing individual in air conditioned area), and seek for medical emergency.

4. CLIMATE CHANGE EFFECTS

Climate change is characterized by changes in the climatic conditions of a region, which persist for a considerable period of time. The World Meteorological Organisation (WMO) and climate scientific communities consider 30 years as the minimum period to smooth out the natural variability of climate (Charron, 2014). Premier climate modelling agencies have generated future projections of climate using Global Climate Models (GCMs) as discussed in detail in successive reports of the Inter-governmental Panel on Climate Change (IPCC). The GCMs simulate the response of global climate system to greenhouse gas (GHG) emissions following four representative concentration pathways (RCP): RCP2.6 scenario that depicts aggressive future climate mitigation; two intermediate scenarios RCP4.5 and RCP6.0; and a business-as-usual RCP8.5 scenario. As such, GCMs are able to simulate global temperatures and temperature extremes with more accuracy than other more heterogeneous variables such as precipitation and wind. Regional climate downscaling techniques are used to produce higher spatial resolution (< 50 km) regional climatic data for performing regional scale impact assessments.

4.1 CLIMATE MODELLING APPROACHES

Global climate models (GCMs) are mathematical models that simulate global coupled land-atmosphere-ocean system, and are used to study the response of climate system to greenhouse gas forcings. Different climate modelling groups have contributed towards providing future projections of global climate. The results of these systematic climate experiments are disseminated primarily through the Coupled Model Inter-comparison Project – Phase 5 (CMIP5). A suite of 50 GCMs, listed in Table 1, have been identified in IPCC (2014) as contributing towards the CMIP5 multi-model ensemble. Canada currently contributes to the CMIP5 ensemble by means of two models: CanCM4 and CanESM2. It has been discussed in IPCC (2014) that the future projections of climate obtained from each of the listed GCMs should be considered equally plausible and no model should be considered better than the other. This introduces significant uncertainty in the projections of future climate, which has been quantified in many studies (Teng et al., 2011).

Table 1. List of Global Climate Models (GCMs) contributing towards the CMIP5 multi-model ensemble.

S. No.	Model name	Country
1	(i) ACCESS1.0; (ii) ACCESS1.3; (iii) CSIRO-Mk3.6.0	Australia
2	(iv) BCC-CSM1.1; (v) BCC-CSM1.1 (m); (vi) BNU-ESM; (vii) FGOALS-g2; (viii) FGOALS-s2; (ix) FIO-ESM v1.0	China
3	(x) CanCM4; (xi) CanESM2	Canada
4	(xii) CCSM4; (xiii) CESM1-BGC; (xiv) CESM1-WACCM; (xv) CESM1-FASTCHEM; (xvi) CESM1-CAM5; (xvii) CESM1-CAM5.1-FV2; (xviii) GFDL-ESM2M; (xix) GFDL-ESM2G; (xx) GFDL-CM2.1; (xxi) GFDL-CM3; (xxii) GISS-E2-R; (xxiii) GISS-E2-H; (xxiv) GISS-E2-R-CC; (xxv) GISS-E2-H-CC; (xxvi) NCEP-CFSv2	USA
5	(xxvii) CMCC-CM; (xxviii) CMCC-CM5; (xxix) CMCC-CESM	Italy
6	(xxx) CNRM-CM5; (xxxi) IPSL-CM5-LR; (xxxii) IPSL-CM5A-MR; (xxxiii) IPSL-CM5B-LR	France
7	(xxxiv) EC-EARTH	Europe
8	(xxxv) HadGEM2-ES; (xxxvi) HadGEM2-CC; (xxxvii) HadCM3	UK
9	(xxxviii) HadGEM2-AO	Korea
10	(xxxix) INM-CM4	Russia
11	(xl) MIROC4h; (xli) MIROC5; (xlii) MIROC-ESM; (xliii) MIROC-ESM-CHEM; (xliv) MRI-ESM1; (xlv) MRI-CGCM3	Japan
12	(xlvi) MPI-ESM-LR; (xlvii) MPI-ESM-MR; (xlviii) MPI-ESM-P	Germany
13	(xlix) NorESM1-M; (l) NorESM1-ME	Norway

Future projections of climate are made in accordance with the projected trajectories of technological, socio-economic and policy development pathways that the global community can adopt in the future. In the CMIP5 multi-model ensemble, future projections of climate are provided for four “representative” concentration pathways (RCPs; van Vuuren et al. 2011) that encompass the range of radiative forcing

projections found in the open literature i.e. from 2.6 W/m² to 8.5 W/m². The RCPs: RCP 2.6, RCP 4.5, RCP6.0, and RCP8.5 correspond to greenhouse gas emission trajectories that would result in an end of 21st century radiative forcing levels of 2.6 W/m², 4.5 W/m², 6.0 W/m², and 8.5 W/m² respectively. The possibility of multiple future growth pathways therefore adds another layer of uncertainty in future projections made by the GCMs.

The typical spatial resolutions at which the simulations are performed within the GCMs range between 1° (~110 km) and 5° (~550 km). To use these projections for local scale impact assessments, the projections are downscaled to obtain higher spatial resolution estimates of future climate. There are two broad categories of downscaling methods that have been used: (1) statistical, and; (2) dynamic. Statistical downscaling models derive statistical relationships between coarser resolution GCM projections and climatic observations, and use the relationships to obtain downscaled climatic projections (Schoof, 2013). The assumption involved is that the nature of the relationships between coarser and finer scale climate estimates will remain unchanged between the historical and future timelines.

On the other hand, dynamic downscaling methods involve the use of Regional Climate Models (RCMs) which are limited-area climate models i.e. they simulate only a subset of global area but at much higher resolution as compared to the GCMs. The typical spatial scale at which RCM simulations are performed is at 25-50 km scale. RCMs generally use atmospheric boundary conditions from the GCMs and generate higher resolution climatology over the region of interest (Xue et al. 2014). One of the known limitations of RCMs is that they rely on GCMs for atmospheric boundary conditions, and the bias associated with GCM simulated boundary conditions is thus transferred to RCM downscaled projections as well. Previous studies have developed statistical procedures to correct for this bias directly in the RCM simulated climatology (Bordoy and Burlando, 2013), or correcting for bias in the GCM boundary conditions before performing RCM simulations (Colette et al. 2012; Bruyere et al. 2014).

4.2 CLIMATE CHANGE IN CANADA – HISTORICAL OBSERVATIONS

The influences of climate change have been detected in Canada. Observational records convey that the average temperatures across Canada have increased on average by 1.3 °C 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).

Similarly, changes in temperature extremes have also been recorded. Wang et al. (2014) analyzed changes in one-in-20 year minimum and maximum temperatures recorded in Canada. They found that between 1911 and 2010, significant increases in extreme indices have been recorded especially in case of extremely low temperatures, and in the Arctic regions of Canada. Alexander et al. (2006), Vincent and

Mekis (2006), and Khaliq et al. (2007) analyzed observed changes in temperature related extreme climate indices in different parts of Canada, and obtained evidence of widespread warming including increases in maximums and minimum temperature extremes, decreases in the numbers of cold days and cold nights, increases in the numbers of warm days and warm nights, decreases in the daily temperature ranges, decreases in the numbers of frost and ice days, increases in the growing season length, and increases in the warm spell durations.

4.3 CLIMATE CHANGE IN CANADA – PROJECTED TEMPERATURES

Climate change is expected to influence considerable changes in temperature patterns across Canada. The time-series of long-term temperature forecasts made by CMIP5 models provided by Environment and Climate Change Canada (ECCC, 2016) suggests a median (across all GCMs considered) warming of approximately 2 °C to 6 °C in average temperatures across Canada for different scenarios as shown in Figure 1. The future trajectories of temperature in Figure 1 have been forecasted for three RCPs: RCP 2.6, RCP 4.5, and RCP 8.5 for the time-periods spanning 20th and 21st centuries. Figure 2 presents the median projected changes in summertime (June-August) temperatures averaged across Canada. Slightly lower summer-time changes have been projected as compared to annual changes which aligns well with a higher warming projected for winter months (not shown).

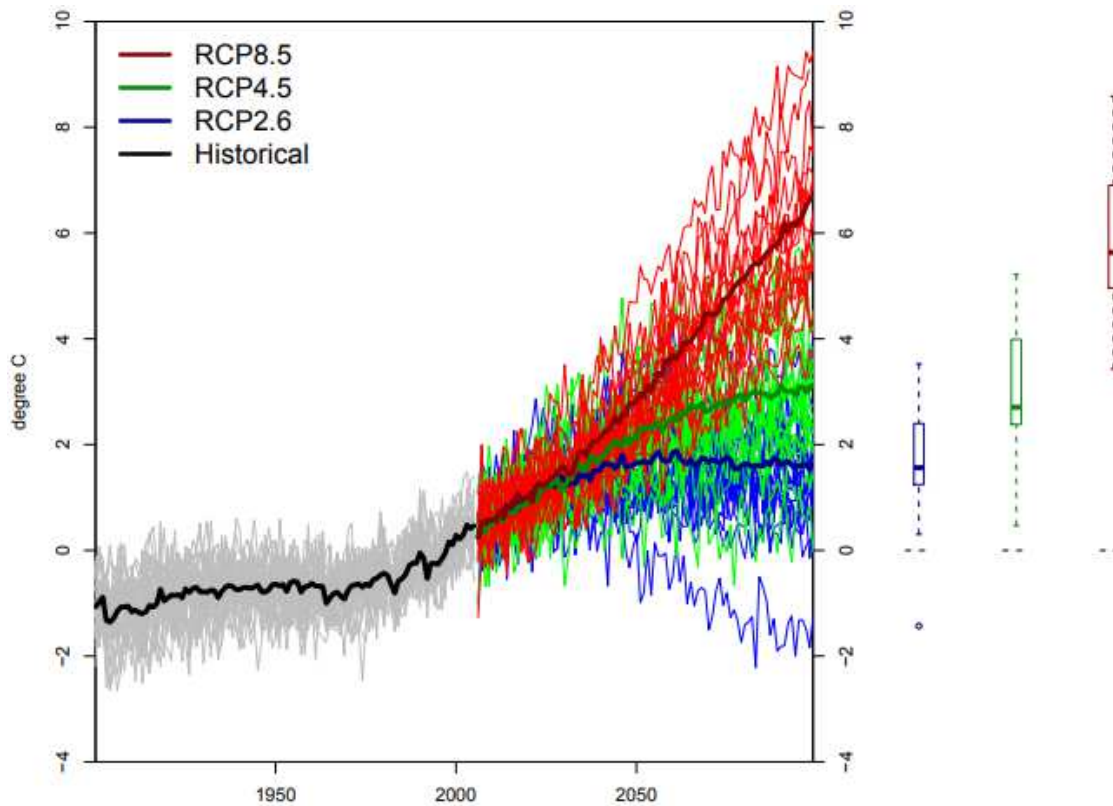


Figure 1. Time-series of projected changes in annual mean temperatures in Canada. The changes were calculated with reference to a baseline time-period of 1986-2005 (Source: <http://climate-scenarios.canada.ca/index.php?page=download-cmip5>)

The projected changes vary spatially, and across different provinces of Canada. A summary of the projected mean changes in annual temperatures across Canada is provided in Table 2 for two extreme RCPs: RCP 2.6 and RCP 8.5. In the table, median changes in average temperatures are provided for individual provinces and for the entire Canadian landmass. As discussed before, the average projected changes in temperature between historical and 2090s timelines, averaged across Canada, range between 2 °C to 6 °C. However, some provinces are projected with higher warming magnitudes than the others. In Table 2, 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.

The spatial heterogeneity in the projected temperature changes can also be noted in the results presented in Figure 2. The Figure shows the color-coded projections of median temperature changes between the baseline historical time-period of 1986-2005 and future timelines: 2050s and 2090s for two extreme RCPs: RCP 2.6 and RCP 8.5. It is evident that the projected increases in temperature are

significantly higher for the northern regions of Canada than the southern regions. Similarly, projected increases are marginally higher in the western regions than in the eastern regions.

Table 2. Projected median changes in average temperatures for individual provinces, and averaged across Canada. 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>).

Region	RCP 2.6		RCP 8.5	
	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 and 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
Yukon Territory	1.8	1.9	3.4	6.2

4.4 PLANNED APPROACHES FOR GENERATING FUTURE CLIMATE DATA

The following steps will be performed to generate the necessary climatic data for undertaking whole building thermal simulations under historical and future projected climates:

4.4.1 Acquisition of downscaled climatic data from ECCC

The climatic projections from the Canadian Regional Climate Model version 4 (CanRCM4) will be the primary source of climatic data that will be used to generate inputs for building simulations. The CanRCM4 data was derived by performing dynamic downscaling of Canadian GCM: CanESM2. The data comprises of fifty members of model projections spanning 1950-2100, each simulated by considering a randomly generated cloud property parameter in the CanRCM4 model.

4.4.2 Extraction of climate projections for different global warming thresholds

The CanRCM4 data obtained from ECCC will be used to extract 31-year long climatic time-series that would correspond to historical, and multiple future scenarios of globally averaged warming ranging from

0.5°C to 3.5°C in 0.5°C increment intervals. In addition to the datasets described in Section 3.4.1, ECCC has also provided centre-years when these global warming thresholds are expected to be reached in the future. Using this information with the datasets described in Section 3.4.1, the 31-year time-series for historical and future time-periods will be extracted for different cities chosen for assessment.

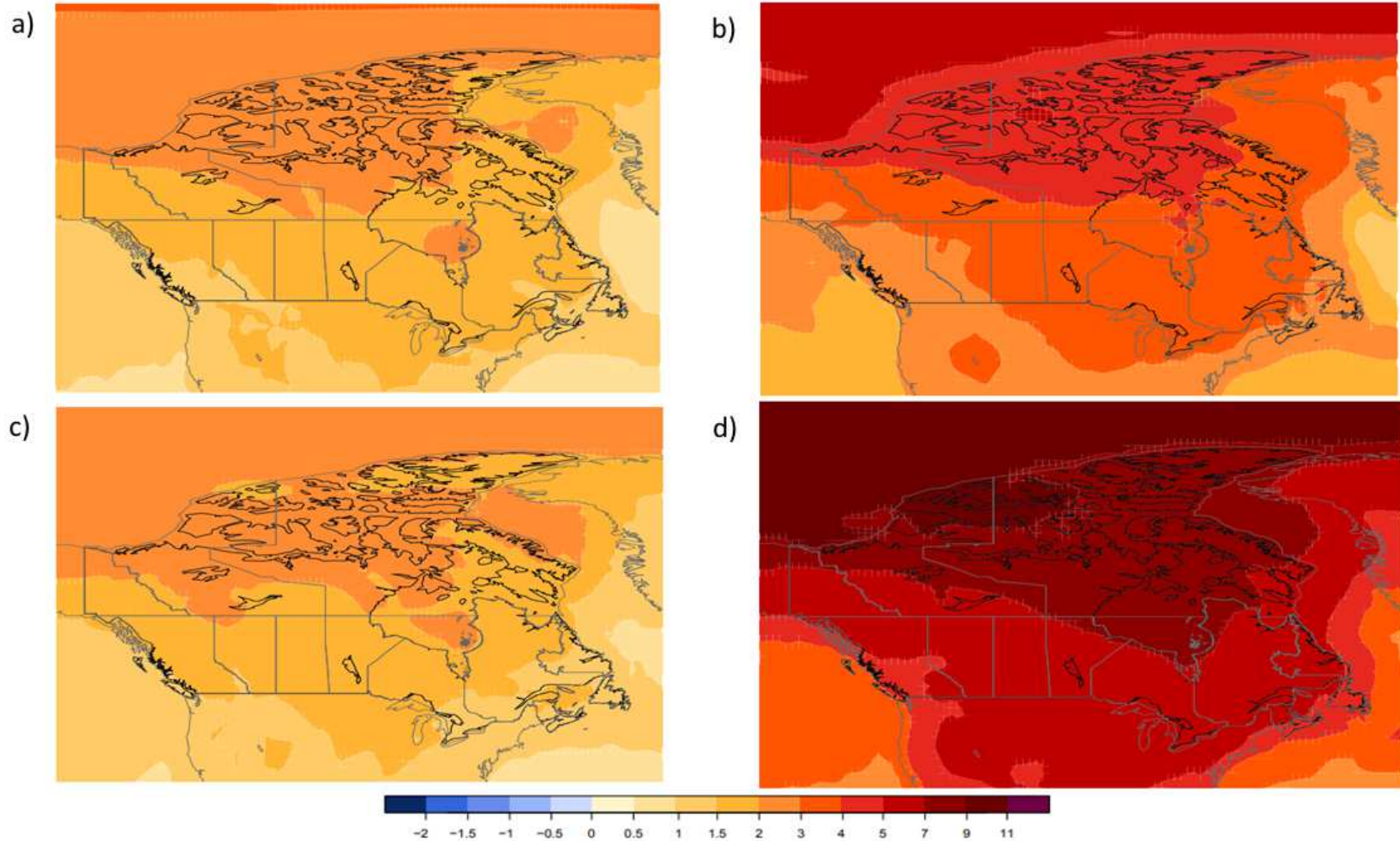


Figure 2. Median changes in average temperatures projected for cases: a) 2050s & RCP 2.6, b) 2050s and RCP 8.5, c) 2090s & RCP 2.6, and d) 2090s & RCP 8.5. Future timelines: 2050s and 2090s represent time-periods: 2046-2065 and 2081-2100 respectively. The changes have been calculated with reference to the baseline historical time-period of 1986-2005 (Source: <http://climate-scenarios.canada.ca/index.php?page=download-cmip5>).

4.4.3 Additional pre-processing steps

It is anticipated that some pre-processing steps may be required to bridge the gap between information available from the CanRCM4 model, and that required for performing building simulations. The following are some of the steps that may be required:

- Bias-correction: Studies have identified the existence of bias between observed climate and that simulated by RCMs (Bordoy and Burlando, 2013). The CanRCM4 data will be checked for the existence of bias; and in the presence of bias, suitable methods will be used to estimate bias-corrected information from the raw CanRCM4 data.
- Disaggregation: Hourly time-series of climate are required for performing building simulations. Out of the 50 sets of CanRCM4 projections, 15 are available in hourly time-steps whereas the rest are available in daily time-steps. The data available in daily time-steps will need to be disaggregated to obtain hourly data. Appropriate disaggregation methods will be used to estimate hourly time-series from the daily time-series of CanRCM4 projections.
- Estimation of direct and diffused radiation fractions: The direct and diffused fractions of incoming solar radiations are generally not provided in the GCM/RCM databases. Suitable methodologies described in the literature (Duffie and Beckman, 1980; Orgill and Hollands, 1977; Morris, 2016; Thevenard, 2010) will be used to obtain this information using the projections of “downward shortwave radiative flux” that are more commonly available.
- Generation of sub 1-km resolution information for select cities: The CanRCM4 projections provided by ECCC have a spatial resolution of 0.44 deg. (~50 km). Higher resolution climatic information is required to identify the spatial heterogeneity of projected climate within the cities to identify the hazard exposure on specific buildings or communities. Modelling at higher resolutions (≤ 4 km) has also been found to improve the modelling accuracy of key urban climate phenomenon such as Urban Heat Island (Prein et al. 2015). However, high resolution modelling also requires significant computational and time resources and therefore sub-km scale simulations will be performed using a Weather Research and Forecasting (WRF) model at select cities within Canada so that the information can be used to prepare overheating hazard maps across the selected cities.

4.4.4 Reference year selection

For the purposes of overheating analysis arising from climate change and EHEs, it is essential to identify years or time-periods when the most intense and frequent temperature extreme events are expected. Some critical aspects that are likely to affect the choice of selected reference years are as follows:

- Definition of extremes: Several definitions of extremes have been used in the past. Some of the most widely used include: annual maximums (Westra et al. 2013); events crossing 95th quantile (Zhang et al. 2017a, b; Scoccimarro et al. 2015); events crossing 98th quantile (Wasko and Sharma 2014); events

crossing 99th quantile (Shaw et al. 2011). Apart from these definitions, the joint CCI/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI) has proposed a set of 27 indices for the assessment of climate change impacts on temperature and precipitation extremes (Zhang et al. 2011). A list of these indices is provided in Table 3. The choice of definition for extremes can be expected to introduce considerable uncertainty in the definition of the hazard (Gaur et al. 2018), and subsequent selection of the reference years.

- Choice of climate variables: Although the focus of the project is on temperature related extremes, the thermal comfort and heat stress indices are also dependent on other climate elements such as humidity, solar radiation, and wind-speed (Li et al., 2018). This would imply that the selection of reference years need to be made taking into consideration not only temperature extremes, but also the joint extremes of, e.g., high temperatures, high humidity, high solar radiation, and low wind-speeds. Therefore joint extremes of these critical climate variables will be taken into consideration when selecting the reference years.
- Choice of Extreme Value Distributions (EVDs): Finally, depending on the selected definition of the extremes, different EVDs such as: Generalized Extreme Value (GEV) for annual maximums, Generalized Pareto Distribution (GPD) for peak-over-threshold extremes can be chosen to fit the extreme values and obtain quantile magnitudes of pre-defined return periods. Sometimes, more than one EVD can be used to fit the same extreme quantiles, and that can introduce another layer of uncertainty in the selection of reference years. For example, Das et al. (2008) simulated extreme precipitation magnitudes by fitting annual maximums using three different distributions commonly used to fit annual precipitation extremes i.e. Gumbel, GEV, and Log-Pearson type 3. They found differences in the performance of the distributions in fitting precipitation extremes and recommended GEV distribution over others for modelling precipitation extremes in the city of London, Ontario. This suggests that the magnitudes of extreme events for pre-selected return periods can also be expected to vary with the distribution selected to fit extreme quantiles.

Table 3. ETCCDI indices recommended for the assessment of climate change impacts on temperature and precipitation extremes (Source: <http://etccdi.pacificclimate.org/>; Zhang et al. 2011)

S.No	Index	Details
1	Number of frost days (FD)	Annual count of days when daily minimum temperature < 0°C
2	Number of summer days (SU)	Annual count of days when daily maximum temperature > 25°C
3	Number of icing days (ID)	Annual count of days when daily maximum temperature < 0°C
4	Number of tropical nights (TR)	Annual count of days when daily minimum temperature > 20°C
5	Growing season length (GSL)	Annual count between first span of at least 6 days with daily mean temperature >5°C and first span after July 1st of 6 days with TG<5°C
6	Monthly maximum value of daily maximum temperature (TX _x)	-
7	Monthly maximum value of daily minimum temperature (TN _x)	-
8	Monthly minimum value of daily maximum temperature (TX _n)	-
9	Monthly minimum value of daily minimum temperature (TN _n)	-
10	Percentage of days when TN < 10 th percentile (TN10p)	-
11	Percentage of days when TX < 10 th percentile	-
12	Percentage of days when TN > 90 th percentile	-
13	Percentage of days when TX > 90 th percentile	-
14	Warm spell duration index (WSDI)	Annual count of days with at least 6 consecutive days when TX > 90 th percentile
15	Cold spell duration index (CSDI)	Annual count of days with at least 6 consecutive days when TN < 10 th percentile
16	Daily temperature range (DTR)	Monthly mean difference between TX and TN
17	Monthly maximum 1-day precipitation (Rx1day)	-
18	Monthly maximum consecutive 5-day precipitation (Rx5day)	-
19	Simple precipitation intensity index (SDII)	-
20	Annual count of days when precipitation ≥ 10mm (R10mm)	-
21	Annual count of days when precipitation ≥ 20mm (R20mm)	-
22	Annual count of days when PRCP ≥ nnmm, nn is a user defined threshold (Rnnmm)	-
23	Maximum length of dry spell (CDD)	Maximum number of consecutive days with daily precipitation < 1mm
24	Maximum length of wet spell (CWD)	Maximum number of consecutive days with daily precipitation ≥ 1mm
25	Annual total PRCP when RR > 95 th percentile of precipitation on wet days (R95pTOT)	-
26	Annual total PRCP when RR > 99 th percentile of	-

5. EXTREME HEAT EVENTS (EHE)

5.1 DEFINITION

Extreme heat events (EHE; also dubbed heat waves) are the result of the natural variability of climate exacerbated by global climate warming (IPCC, 2014). Extreme heat events are characterised by their intensity, duration and frequency of occurrence. The EHE characteristics are very important in studies that evaluate the risks of EHE. A proper definition of EHE that incorporates the EHE characteristics is also necessary to properly assess the health effects arising from exposure to elevated temperatures (Xu et al., 2017). 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). The word ‘rare’ inherently refers to the event relative intensity as compared to the reference average intensity over the period of time being considered (e.g., months, seasons) at the locality. The EHE intensity is expressed in temperature (e.g., daily maximum, minimum or average temperature), or a combination of temperatures and other confounding climate variables (e.g., relative humidity, wind speed, solar radiation or other relevant climate parameter). The event duration, be it days or weeks, is not specified in this definition. For practical applications there is no specific definition of EHE which is accepted worldwide (WHO, 2009; Gachon et al., 2016; EPA, 2016). The challenge resides particularly in the selection criteria of the threshold values of intensity and event duration. The event frequency is, however, statistical and computed as the inverse of the probability of occurrence (or cumulative frequency distribution) of the intensity variable and the specified threshold value (see Figure 3). The duration is also indirectly included in the probability density of the threshold value. For example a long EHE with a constant intensity would have a higher probability density than the same event that occurs over a shorter period of time. In other words, an event with a threshold value of a given percentile would have the same effect as an event with a lower percentile but with a higher threshold value. The product of the EHE intensity and duration indicates the severity of EHE. For public warning against EHE, the duration of EHE should therefore be specified to reflect the accuracy of the weather forecast to avoid false positives. Weather forecasts of more than three days are usually not accurate (Gachon et al., 2016). Given this challenge, the climate and health organisations and scientific communities have used various definitions of EHE (Vaidyanathan et al., 2017; EPA, 2016; Gachon et al., 2016). These definitions may be grouped into three categories: climate (or meteorological) based, impact based or a combination of climate and impact based definitions. For all definitions, the EHE duration is arbitrarily fixed to two or more days.

The climate based definitions express the intensity as a function of the climate variables with thresholds that can be absolute or relative, or a combination of both. The EHE intensity uses the maximum daily temperature, minimum daily temperature, average daily temperature, or combination of the daily temperatures (Met Office, 2015; Laaidi et al., 2012; Medina-Ramon and Schwartz, 2007). The absolute thresholds (e.g., maximum

temperature of 29°C to 40°C) are determined from historical climatology (over a 30 year period), and their corresponding frequencies of occurrence are computed from the probability density distribution (NASEM, 2016). The relative thresholds are arbitrarily chosen from either the percentile of exceedance (e.g., 90th to 99th; WHO, 2009) or deviation from the historical mean value (e.g., 5°C to 10°C). The disadvantage of the absolute threshold method is that the thresholds are fixed for any climate and therefore the acclimatization of the population to warm events is not considered. Similarly, for the relative threshold method, which can be applied to any climate, there is no fixed percentile from which EHE and their effects can be discerned that would work for any given climate. Due to these limitations, alternative definitions for EHE use a combination of absolute and relative thresholds for a particular location (Guo et al., 2017). Recently, Russo et al. (2015, 214) developed a new heat wave magnitude index daily (HWMId) that combines the magnitude and duration of a heat wave in any climate for a given location. The index defines the heat wave as an event that occurs over at least three days with daily maximum temperatures above the 90th percentile. The magnitude of the heat wave is computed as the ratio between the difference in the daily maximum temperature and its 25th percentile over the difference between the 75th and 25th percentiles. The percentile is computed using the reference historical data for 1981-2010. HWMId is computed as the sum of the heat wave magnitudes over the number of days of each month for the reference period. The index was applied to Europe and produced the known heat waves that occurred over past decades back to 1950.

The impact-based definitions of EHE are based on the effects of EHE on the comfort and health of the population. Indices for physiological heat stress together with epidemiological studies on all-cause (non-accidental) mortality data are used to establish the thresholds for the EHE intensity. Mortality-based EHE intensity uses the daily maximum temperature, daily average temperature, or combination of daily maximum or average and minimum temperature (Gachon et al., 2016). The threshold values are chosen to correspond to the onset of excess mortality above the seasonal average (Hajat and Kosatky, 2010; Zeng et al., 2016). Various threshold values are therefore determined depending on location, delineating the variability of mortality data with the local climate and vulnerability of the population to EHE (see Figure 4). This approach is, however, not accurate in delineating EHE due to many reasons (EPA, 2006; Cheng and Berry, 2013): (1) not any lethal temperature is an EHE; in fact lethal temperatures that are not associated with EHE frequently occur (Mora et al., 2017); (2) The actual exposure temperature within a building is different from the outside environment given the fact that most people spend up to 90% of their time indoors (IOM, 2011); Information given in (1) and (2) might explain why some mortality studies found that the onset of excess mortality occurred at temperatures at the limit between thermal comfort and discomfort (25 to 28°C), particularly in cold or temperate climates (Casati et al., 2013); (3) Mortality has many confounding variables such as population vulnerability (e.g. sex, age, prior illnesses, socioeconomic status), usage of air conditioning, and degree of air pollution; it is therefore very difficult to isolate the effect of outdoor temperature on mortality given the occurrence of an EHE.

Physiological thresholds for heat stress use the universal thermal comfort and heat stress metrics to establish the limit when EHE are perceived as warm, hot, very hot, or become dangerous to health (Chindapol et al.,

2017; Blazejczyk et al., 2012). These indices are based on the heat balance of a human body. Thermal comfort indices are subjective (based on the average votes of a large population) and include the popular Fanger's Predicted Mean Vote (PMV) index and the adaptive comfort for naturally ventilated buildings (ASHRAE, 2017). There are over a hundred metrics for heat stress (Epstein and Moran, 2006), and these are either subjective (based on the PMV scale) or purely physiological (e.g., thresholds of skin wettedness, skin and rectal temperatures, and sweat rate). Some of the most commonly used indices include the Standard Effective Temperature (SET), Perceived Temperature (PT), Effective Temperature (ET), Physiological Equivalent Temperature (PET), and Universal Thermal Climate Index (UTCI). Various thresholds for EHE are thus established according to the human body model that varies from a simple one node model (Fanger's single skin temperature) to more complicated multi-nodes models. These models are, however, developed for healthy and average adult people, and therefore cannot be applied to vulnerable populations (e.g. children, seniors, sick people). Furthermore, the newly developed models for healthy individuals (such as UTCI, PET, and others) still need further work to these being generalized for use in different climates.

The EHE definition that combines the climate and impact based thresholds (also called bio-meteorological) usually use a combination of weather variables (e.g. temperature, relative humidity, wind speed, solar radiation) into an empirical index that relates to an individuals' perceived heat. Such indices include Apparent Temperature (AT), Humidex (H), Heat Index (HI), Discomfort Index (DI), and Wet Bulb Globe Temperature (WBGT). Details of these indices are found in Section 6 of this report. Absolute or relative thresholds of these indices (based on percentiles) are used to discern EHE and their effects on human health.

The forgoing analysis shows that a universal definition and metric for EHE is a complex matter to determine given the fact that EHE are transient in nature and their effects on human comfort and health depend on the previous (e.g., nighttime) and actual exposure to the thermal conditions, and are confounded by many climate and non-climate factors. It is, however, well known that the physiological acclimatization of individuals to climate and the effects of temperature on human comfort and health are well established, particularly for healthy individuals. As human health is affected by absolute temperatures, this suggests that that the human heat balance is likely the right approach to establishing universal absolute temperature thresholds for the definition of EHE for any climate and that accounts for climate adaptation. Threshold temperatures may be determined from laboratory or field studies to cover healthy and vulnerable population categories. While comfort and health metrics for healthy individuals are available those for vulnerable people have yet to be developed. Results from recent encouraging studies (Rida et al., 2014; Ma et al., 2017) indicted that heat balance models have been developed for the elderly that account for age, gender and ethnicity whereas thresholds(or scales) for heat induced stress of vulnerable people have not yet been developed.

Given the absence of proper comfort and heat-stress health metrics for vulnerable people, climate and health organisations around the world and local jurisdictions have adopted EHE definitions that are based on the local prevailing climate and population vulnerability (EC, 2018; EPA, 2016; WHO, 2009). To issue public warnings regarding heat waves in various provincial climatic regions Environment Canada (EC) has adopted the metrics

of *Humidex*, daily maximum temperature, or combination of the daily maximum and minimum temperatures (EC, 2018). Table 4 summarizes EC's heat definition and heat warning thresholds.

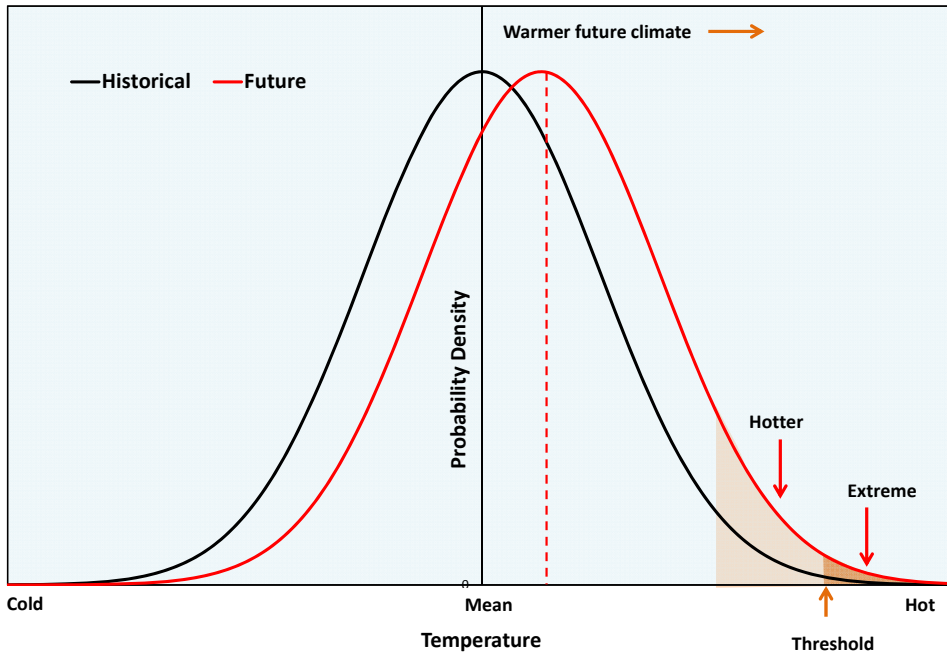


Figure 3. Temperature distribution of climate (30 year period) and extreme heat events

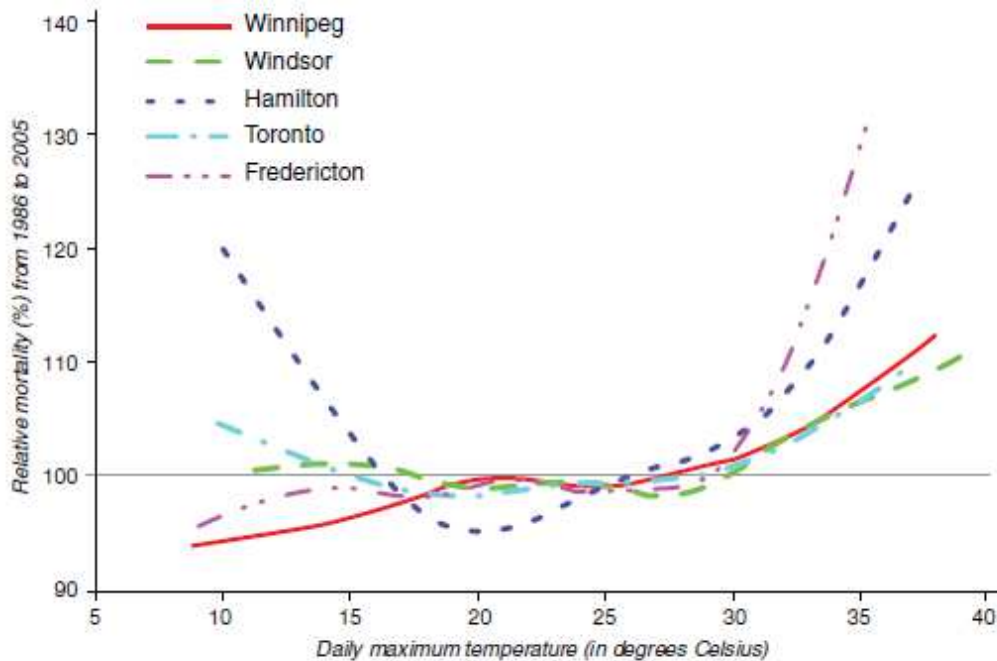


Figure 4. Non-traumatic mortality-temperature profiles during the summer seasons (June-August) of 1986-2005 for selected Canadian cities (Source: Casati et al., 2013)

Table 4. Environment Canada's heat alert criteria for public warnings (T_{max} = daily maximum temperature, and T_{min} = daily minimum temperature)

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

5.2 HEALTH IMPACT OF EHE

EHE arising from climate change is a major hazard to human health (HC, 2011). Continuous exposure to hot temperatures over several days strains the human physiological system to its upper limit, potentially leading to health issues or death. Mortality (death) and morbidity (sickness) are the leading outcomes of EHEs. The effects of EHE are exacerbated by other climatic factors such as the local climate type (cold, temperate, hot), high humidity as well as non-climate factors such as air pollution, and the health and socio-economic status of the local population. Vulnerable people whose physiological systems are not fully developed (children) or weak due to aging or sicknesses will suffer the most from EHEs. Furthermore, vulnerable people accustomed

to cold or temperate climates are under a higher risk of EHEs than those accustomed to warm climates (Medina–Ramon and Schwartz 2007).

5.2.1 Mortality

EHE-related mortality has been extensively studied around the world. Worldwide, EHE are responsible of about 150,000 deaths annually (Patz et al, 2005; Song et al., 2017). Throughout the past century, EHE have occurred numerous times in many places around the globe. However, the most deadly events occurred in North America and Europe (Mora et al., 2017). The Chicago heat wave in 1995 was responsible for 692 excess deaths (Kaiser et al., 2007). The heat wave covered the period from June 22 to August 10 with high humidity and daily temperature peaking at 40°C. Most deaths were amongst the elderly and socially deprived. The heat wave was also accompanied by extended and widespread power outages (IOM, 2011). The heat wave of August 2003 in Western Europe was the most deadly event in Europe since 1950, resulting in more than 70,000 excess deaths in 16 countries (Robine et al., 2008). France was seriously hit with 15,000 deaths over eight consecutive days of extreme heat with peak temperatures attaining 40°C. In the summer of 2006, a global and massive heat wave hit both North America and Europe. In France, this heat wave was the second deadly event after that which occurred in 2003. It lasted 18 days with a peak temperature of 40°C in Paris, resulting in an excess mortality of 2065 deaths (Fouillet et al., 2008). In the summer of 2010, an unprecedented heat wave struck Russia and Eastern Europe with soaring temperatures during the day (peaking at 40°C, or 12°C above the average temperature) and night over 12 consecutive days (Cairns, 2012). The heat wave was responsible for more than 55,000 deaths in Russia alone and was accompanied by massive wildfires that destroyed many agricultural crops.

Canada has also been struck by many heat waves over the past decades. In Toronto alone an average of 120 annual excess deaths were observed between 1954 and 2000. In the summer of 2005 Toronto experienced 41 hot days some having peak temperatures reaching 30°C (HC, 2011b). 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).

Mortality studies have focused on investigating the relationship between all-cause (excluding accidental) and cause-specific excess deaths and the outdoor daily temperature (i.e. maximum, minimum, average) and air pollution data (i.e. concentrations of ozone and particulate matter) as confounding factors. The studies were done for specific locations that covered entire climate regions or metropolitan cities. Temperature and air pollution data were taken from the weather stations closest to the location under study. Mortality counts for the period under study were collected from local medical death registry databases and compared to the mortality counts of a reference period to determine data for excess mortality. Since the effect of temperature on

mortality is not instantaneous, several periods of time lag following the EHE were considered, varying from one day to a few days and in some instances, to a period of weeks. Many studies found that the mortality-temperature profile follows a U, V or J-shaped profile, potentially indicating two critical threshold temperatures for the cold and heat extreme temperatures, beyond which the effect of temperature on mortality starts to appear (see for example Figure 4).

There are many mortality studies worldwide. Medina-Ramon and Schartz (2007) conducted a cross-over study on the effects of cold and hot temperatures and ozone concentration on mortality and population adaptation in 50 USA cities during 1989-2000. The daily average temperature in the covered cities ranged from 18.5°C to 32.1°C for the hot months. The study found that heat related mortality varied from city to city, with the largest effect was observed in cities with milder summers (daily average temperature around 19.8°C at 25% percentile). The population living in cities in cold climate zones were found to be fully acclimatized to cold temperatures, but not to heat. Acclimatization was attributed to the ubiquitous use of central heating systems in cold climate regions compared to less usage of air conditioning in warm or hot climate regions. Ma et al. (2014) and Li et al. (2016) analysed the mortality-temperature data for large Chinese cities in various climate regions (i.e. hot, temperate, cold). The mortality-temperature data was found to follow U, V, W, J or inverted J-shapes, and varied from city to city as expected. The strongest effect of temperature on mortality appeared within two to three days, and thereafter quickly decayed within a week. The higher the daily temperature the shorter the time-lag. The optimum daily average temperature at which the mortality was the lowest varied from city to city, with a city-average value of 21°C. Basu (2009), Hajat and Kosatky (2010) and Song et al. (2017) reviewed literature on mortality-temperature data in America, Europe and Asia. Air pollution and the vulnerable population group were included in the mortality analysis as confounders or effect modifiers. From the reviews it was found that high temperatures increased the risk of mortality for the vulnerable population having diabetes and cardiovascular, respiratory and cerebrovascular diseases and that portion of the vulnerable population being elderly, children, infants, and those with a lower socioeconomic status. Children and infants were identified as being the most vulnerable to extreme heat. Air pollution data was found as a confounder for some places but not for others. Heat thresholds were higher in communities near the equator or in hot climates suggesting some level of population adaptation to heat stress. Guo et al. (2017) conducted a multi-country and community study on the effect of heat waves on mortality in various climatic zones (i.e. cold, moderate cold, moderate hot, and hot). Mortality data (26 million) were collected from 400 communities in 18 countries based on the heat wave definition that used various threshold temperatures from the daily mean temperature percentile (i.e. 90th, 92.5th, 95th, and 97.5th) with a duration of two, three, and four days. Periods for time lag varied from 0 to 10 days. The study found that the higher the temperature thresholds the more visible the effect of temperature on mortality. However, the duration of the EHE did not modify the impact. The effect of temperature on mortality appeared immediately and lasted three to four days in all countries. At a community level, the daily average temperature was found to be a better metric in defining heat waves than the daily maximum or minimum temperature. However, at the country level, there was no difference amongst metrics for the daily average, maximum or minimum temperature. Mora et al. (2017) conducted a global analysis of

documented lethal heat effects on human health for the period 1980 to 2014. The study covered 164 cities in 36 countries. The study identified global thresholds of daily mean temperature and relative humidity beyond which mortality starts to appear (see Figure 5). The analysis showed that about 30% of the world's population is currently exposed to climatic conditions that exceed these deadly thresholds for at least 20 days. Future climate change by 2100 would bring this percentage to 48% (assuming a low emission scenario, RCP2.6) or to 74% (assuming a high emission scenario, RCP8.5).

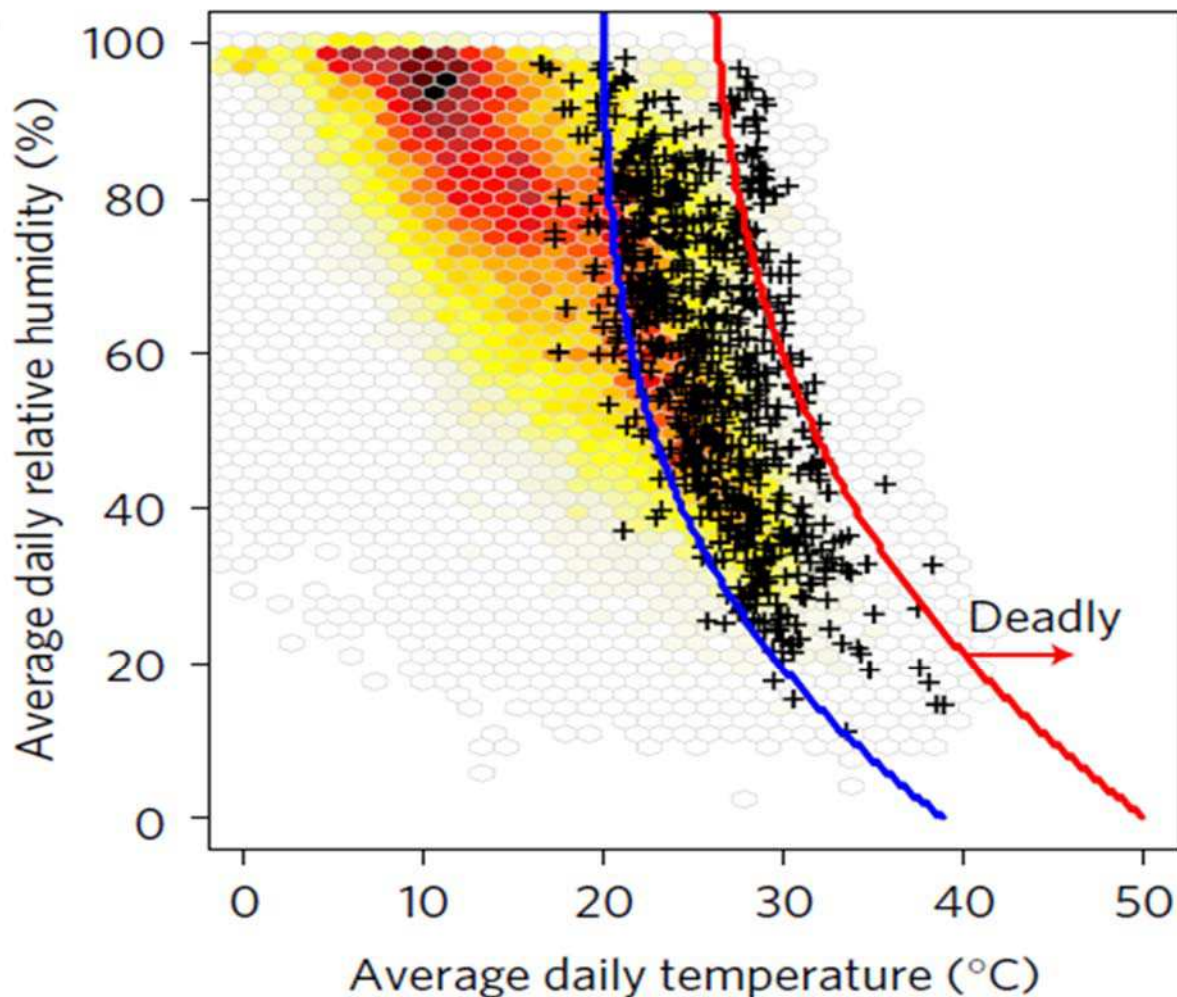


Figure 5. Thresholds of the mean daily air temperature and relative humidity during lethal heat events (black crosses) and during non-lethal heat events (red to yellow dots). Blue line is the threshold that best separates lethal and non-lethal heat events, and the red line is the 95% probability threshold; Areas to the right of the thresholds are classified as deadly and those to the left as non-deadly (Source: Ma et al., 2017).

In the Canadian context, there are several studies on mortality conducted in the past decades. Cheng et al. (2008 a, b) conducted a study on the effect of temperature and air pollution on mortality in south-central Canada (e.g. the cities of Montreal, Ottawa, Toronto, Windsor) based on historical climate data and future projections. The future climate data was based on five GCMs combined with regional statistical downsizing regression techniques. The annual excess mortality averaged over the period 1954-2000 was estimated to be over 1000 deaths (95% confidence interval) for Montreal and Toronto, and less than 462 for Ottawa and Windsor. An estimate of 20% of this mortality rate was attributed to EHE and the rest to air pollution, from which ozone had the highest (33%) impact. Based on the current data, future projections for mortality would double by year 2050, and triple by year 2080. Doyon et al. (2008) developed a regression model that links the daily excess all-cause (non-accidental) mortality with the daily mean temperature based on the local historical climate data of 1981-1999. The model was then used to predict the effect of future climate projections on mortality in three Quebec cities (i.e. Montreal, Quebec city, Saguenay). GCMs combined with regional statistical downsizing regression techniques were used to generate future climatic data for two emission scenarios. The simulations showed that by year 2080 future climate change would increase the summer mortality from 3 to 10%.

Goldberg et al. (2011) conducted a study on the effect of the urban heat island (UHI) temperature on non-accidental mortality in Montreal, Quebec, in the summer of 1990-2003. They examined the relationship between the daily mortality data with the daily average air temperature obtained from local airport weather stations and the satellite-based Land Surface Temperature (LST). Although LST is different than the local air temperature, the LST may indicate the significance of urban heat island effects in the locality under study. The study found that mortality was higher in areas with higher LSTs. Of the deaths arising from UHI temperatures in Montreal, 78% of the deaths were attributed to elderly above 65 years old. In another study, Goldberg et al. (2011) assessed the relationship between all-cause and cause-specific mortality and daily maximum temperature in Montreal for the period 1984-2007 based on different periods of time lag (i.e. 0 to 30 days). The population had a reduced capacity for adaptation to heat as there was little penetration of the use of air conditioning in homes (about 25.6% province wide). Air pollution in terms of ozone and nitrogen oxide concentrations was accounted for in the analysis as confounder. The daily maximum temperature for the period studied varied from 23.9 to 36.2°C. The daily mortality varied non-linearly with temperature. For a time lag period of 30 days, the cumulative daily mortality increased by 28.4% when the daily maximum temperature increased from 22.5 to 31.8°C. The optimum temperature beyond which the mortality increases was found to be 27°C (91% percentile). Vanos et al. (2015) used synoptic weather data classification to study the synergetic effect of temperature and air pollution (i.e. ozone and particulate matter) on non-accidental mortality for the period of 1981-2008 in 12 Canadian cities (i.e. St-John, Halifax, Quebec city, Montreal, Ottawa, Toronto, Windsor, Winnipeg, Regina, Calgary, Edmonton, Vancouver). The results confirmed the finding of previous studies for which the effect of air pollution on mortality is found to be significant. Chen et al. (2016) assessed the effects of cold and hot temperatures on non-accidental mortality in the province of Ontario for the period of 1996-2010. An analysis of mortality was undertaken in each census division (total of 27) and then

pooled across Ontario, covering approximately 352,818 deaths having an average age of 76 years. The average temperature ranged from 15.9 to 21.7°C. The study found that heat increased the respiratory-related deaths, and the same day (zero time lags) non-accidental mortality was, on average, four excess deaths (or 2.5%) for each 5°C increase in the daily average temperature. Auger et al. (2015) studied the association of ambient heat with sudden death of infants in Montreal, for the period of 1981-2010. The study found that if the daily maximum temperature was in excess of 29°C on the same day or a day before the death occurred, this was strongly linked to sudden death syndrome in infants of ages 3 to 12 months.

5.2.2 Morbidity

Compared to mortality, morbidity studies have been very limited due to the lack of publicly available data. Existing studies have used various metrics for morbidity such as hospital emergency visits, hospitalisation, hospital admission, emergency calls, medical services, ambulance call-outs, and outpatient visits. Li et al. (2015) conducted a literature review on the effect of EHEs on morbidity worldwide for the period of 1985-2014. About 33 studies were selected for the analysis. Most studies found a short term negative impact of EHEs on morbidity, particularly for the elderly, children, and those persons with existing chronic diseases. Lavigne et al. (2014) conducted a study on the relationship between heat waves and emergency room (ER) visits for the cardiovascular and respiratory diseases that occurred in Toronto hospitals for the period of 2002-2010. The study covered 292,666, and 562,738 visits for cardiovascular and respiratory diseases, respectively. The study found that persons with comorbid diabetes were vulnerable to the short term effects of EHEs and had increased risk of being admitted to a cardiovascular emergency room (ER). Similarly, EHEs increased the risk for respiratory ER visits for persons with comorbid chronic respiratory diseases. Xu et al. (2017) recently conducted a study on the effects of EHEs on infant's hospital admissions in Brisbane, Australia, for the period of 2005-2015. The study found that EHEs as defined by the daily mean temperature above the annual 97th percentile and duration of two days or more was highly associated with infant hospital admission.

6. RISK FACTORS FOR EHE-RELATED HEALTH

EHEs affect all categories of people of any ethnicity around the world from children to young adults and seniors, healthy as well as sick people. Vulnerable people are of primary interest since they are the first to succumb to the effects of EHEs. There are also other risk factors that may exacerbate the effects of EHEs on the population's health, socio-economic status and as well, environmental conditions (other than temperature).

6.1 VULNERABLE PEOPLE

Vulnerable people are at a higher risk to the effects of EHEs than healthy people. Vulnerable people are defined as a category of a population who are susceptible to heat stress, or have reduced mobility and economic ability to adapt to or mitigate the effects of heat stress in their indoor environment (IOM, 2011). They include:

Seniors — People above the age of 65 make up about 17% of the total Canadian population (Table 5). They are the most affected by EHE (HC, 2011a; Astrom et al., 2011). Compared to healthy people, seniors have a reduced ability to acclimatize and are less sensitive to heat and thirst. In other words, seniors have lower sweating rate, blood flow to the skin and body extremities, cardiac output (blood volume), vasodilation of blood vessels, and metabolic rate (due to reduced muscle mass), and a higher temperature threshold for sweating, and body fat percentage (Van Hoof et al., 2017; Roelofsen, 2017). As a consequence, the bodies of seniors 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 young adults to compensate for their lower metabolic rate and reduced peripheral blood flow (Van Hoof et al., 2017; Schellen et al., 2010; Parsons, 2003). Seniors may also have less capacity to behaviourally adapt to the environmental conditions.

Children — Infants and children (under 15 years old) make up about 17% of the total Canadian population (Table 5). They are the second most portion of the population affected by EHEs (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 EHEs (HC, 2011a). Furthermore, infants and young children are reliant on caregivers to make any adaptation (e.g., dressing, drinking water, opening windows) to themselves or surrounding environment to reduce the risk of EHEs.

Sick people — The impact of EHEs on people's health is further exacerbated for those with a prior sickness 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, 2011A; 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. SES factor was an evident mortality cause in the 1995 Chicago (Kaiser et al., 2007) and 2003 European (Robine et al., 2008) heat wave events (IOM, 2011). The SES variables are usually grouped into one SES index, which is developed based on dissemination and metropolitan area census data. SES index is used for urban neighborhood health planning and to target vulnerable people during EHEs. Pampalon et al. (2009) developed the Material and Social Deprivation Index (MSDI), which is widely used in Quebec for health planning. The Canadian Institute of Health Information developed an analytical tool to calculate the MSDI for any Canadian city based on the national 2006 census data (CIHI, 2018). Bell and Hayes (2012) developed VANDEX for Vancouver neighborhoods, British Columbia.

Physically active people — These include 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 EHEs as it compromises the blood flow through the muscles with that needed for skin surface cooling, and affects the sweating rate due to insufficient replenishment of water (causing body dehydration).

6.2 ENVIRONMENT FACTORS

Environmental conditions play a significant role in the heat balance of the human body. Beside temperature, there are other factors that confound the effects of EHEs on health of people, including:

- Relative humidity. This is a major factor that affects the effectiveness of the evaporative cooling of the body skin surface from the release of sweat. Thus high humidity levels increase the risk of hazardous EHE health effects.
- The flow of air from a ventilation fan when either outdoors or indoors, increases skin surface cooling and thus reduces the risk of hazardous EHEs health effects.
- Outdoor exposure to solar radiation increases the mean radiant temperature and thereby increases the risk of hazardous EHEs health effects.
- In cold climate regions, local climate conditions may affect the acclimatization of the population, particularly in the early days of summer.

6.3 COMMUNITY FACTORS

Community factors that may increase the risk of hazardous EHE health effects include:

- Population density for seniors and children. Seniors and children (under 14 years old) make up of 34% of the Canadian population (Table 5). Seniors and children in cosmopolitan cities make up about 8 to 19% of their respective provincial population. Toronto (Ontario), Montreal (Quebec) and Vancouver (British Columbia) cities are with the highest population density in Canada, and are therefore more susceptible to mortalities during EHEs.
- Urban heat island (UHI) effects which are present in large and dense cities. The temperature difference between cities and country sides may reach up to 12°C particularly during night (Gachon et al., 2016), reducing therefore the effectiveness of nighttime ventilation cooling in buildings.
- Urbanisation that takes more green land spaces, which are essential to cool the atmosphere and reduce UHI effects.
- Air pollution (concentration of ozone and particulate matters, smog). EHEs increase chemical reactions, resulting in more production of air pollutants, particularly in industrial areas.
- Limited community cooling centers that vulnerable people would use during EHEs

- Affordable transportation networks that vulnerable people would use to get to community cooling centers during EHEs.

Table 5. Distribution of Canadian population taken from the 2016 census (Source: StatCan, 2018; <http://www12.statcan.gc.ca/census-recensement/2016/dp-pd/hltfst/as/Table.cfm?Lang=E&T=12&type=1>)

Location	Total	% ^(*)	0 - 14 years	%	≥ 65 years	%
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

6.4 BUILT ENVIRONMENT FACTORS

The built environment affects the indoor thermal conditions and air quality. 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. Risk factors related to the built environment that may exacerbate the EHE health effects include:

- Non air-conditioned buildings. In Canada, about 39 to 50% of residential buildings do not have air conditioning (Tables 6 and Table 7). 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-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.
- Buildings with high occupant density (e.g., social housing) which may result in poor indoor air quality and respiratory health issues.
- Multi-unit residential buildings (MURBs). Upper floors of MURBs were 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, cross ventilation in single aspect (one glazed facade) apartments may be limited, thus increasing the risk of space overheating in non-air-conditioned buildings. In addition, upper floors may limit the movement of vulnerable people to community cooling centers during EHEs (Vellei et al., 2017; Touchie et al., 2016; 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	Man./Sas.	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. METRICS FOR HEAT-RELATED HEALTH STRESS

The effect of heat on the thermal comfort and health of people is a mature topic. There are more than 100 different metrics of varying complexity (Walls et al., 2015; Blazejczk et al., 2013). Havenith and Fiala (2016) listed the chronological development of 35 most commonly used indices for different applications. The metrics were developed for healthy adults (average age 35 years) under steady state environmental conditions. Thermal comfort metrics focus mainly on the comfortable (neutral) thermal conditions and the borderline between comfort and discomfort where an individual's characteristics, such as age and gender, do not make any significant difference (Parsons, 2003; Rida et al., 2014). Thermal comfort metrics are universally accepted in the design of air conditioned buildings. However, thermal stress metrics go beyond the neutral thermal conditions to conditions that may result in serious health issues or even death. Individual characteristics (e.g. gender, age, mass, height, degree of obesity, and clothing) and the propensity of an individual to acclimatize heat stress may also have a significant effect (Roelofsen 2014, 2017). Studies have indeed found that the elderly showed a different percentage of dissatisfaction for a given temperature range deemed comfortable as compared to young adults (Hwang and Chen, 2010). The elderly also respond differently having a lower tolerance to thermal conditions out of the comfort range (Roelofsen, 2017; Van Hoof et al., 2017; Rida et al., 2014). There are currently no universal metrics for the effects of heat stress on human health. Both thermal comfort and heat stress metrics are based on four primary approaches: (1) subjective response (or thermal sensation) of people to imposed indoor thermal conditions; (2) physiological response to heat; (3) experimental (empirical) studies, and; (4) epidemiological studies.

7.1 THERMAL COMFORT METRICS

Thermal comfort metrics were developed for a large group of people of all genders and for young adults as well as the elderly based on subjective studies in enclosed air conditioned spaces under steady state conditions (Parsons, 2003). ASHRAE Standard 55 (ASHRAE, 2017) defines the thermal comfort as “*the condition of mind that expresses satisfaction with the thermal environment*”. The metrics for the average comfort (excluding local discomfort for exposed body parts) include:

Predicted Mean Vote (PMV) — PMV, developed by Fanger (1970), is the most accepted thermal comfort metric amongst practitioners and is specified in many international standards (e.g., ASHRAE 55- 2017; EN15251-2007; ISO 7730-2005; CSA Z412-00 (R2016)). The metric scale is expressed numerically from -3 to +3 corresponding to thermal sensations of: cold (-3); cool (-2); slightly cool (-1); neutral (-0.5 to +0.5); slightly warm (+1); warm (+2); and hot (+3) (ASHRAE, 2017). PMV is calculated based on a one-node (average skin temperature) bioheat model where the skin wettedness (percentage of skin covered by sweat) and skin average temperature are correlated to the metabolic rate of the person’s activity level. The model is governed by six parameters including: activity level (metabolic rate), body insulation level; air temperature, Mean Radiant Temperature (MRT), relative humidity, and air speed. The neutral conditions of PMV correspond to the physiological state of the body, where the body: is in heat balance; has minimum or no sweating; average skin temperature is within the comfort limits, and; does not exhibit any local thermal discomfort (Parsons, 2003). 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%). Although the use of PMV is suitable for indoor conditions, some studies have, however, adapted PMV to outdoor conditions by modifying the MRT temperature to include solar and thermal radiation (Walls et al., 2015; Jendritzky and Nübler, 1981; Jendritzky et al., 1990). For typical indoor summer conditions (light summer clothing = 0.5 clo; metabolic rate = 1 met; still air speed = 0.15 m/s; MRT = air temperature; Parsons, 2003), the corresponding upper limit for the comfort temperature is 27.85°C and 27.35°C for indoor relative humidity of 40 and 60%, respectively (calculation done using the online ASHRAE CBE comfort tool: <http://comfort.cbe.berkeley.edu/>; accessed in January 2018).

Adaptive Comfort — Adaptive comfort was developed for buildings occupants residing in naturally ventilated buildings (residential, office, and industrial building) working in sedentary activities (metabolic rate from 1 to 1.3 met) and with the prevailing outdoor monthly mean temperature between 10°C to 33.5°C (ASHRAE, 2017). The comfort temperatures for adaptive comfort are higher than the static thermal comfort due mainly to the adaptation of people, including behavioral, physiological and psychological adaptation. The upper and lower comfort temperature range ($T_{c,up}$, $T_{c,lo}$) corresponding to the 80% acceptability limit is linked to the prevailing outdoor monthly mean temperature (T_{omm}) through the following relation (ASHRAE, 2017).

$$\text{Upper 80\% acceptability limit } T_{c,up} (^{\circ}\text{C}) = 21.3 + 0.31 \cdot T_{omm} \quad (1)$$

$$\text{Lower 80\% acceptability limit } T_{c,lo} (^{\circ}\text{C}) = 14.3 + 0.31 \cdot T_{omm} \quad (2)$$

The European standard EN15251-2007 (CEN, 2007) for adaptive comfort in free-running buildings (developed in Europe from measurement of office buildings) uses a different correlation based on the actual weekly running average temperature. The comfort temperatures are published for three categories of occupant expectation in buildings: I - for buildings with sensitive and fragile people (PMV = ± 0.2 ; PPD = 6%); II - for new or retrofitted buildings (PMV = ± 0.5 ; PPD = 10%); and III - for old buildings (PMV = ± 0.7 ; PPD = 15%). The upper comfort temperatures given in EN15251 are a few degrees Celsius higher than those provided in ASHRAE -55 assuming the same monthly average temperature. Table 7 offers a summary of the ASHRAE-55 and EN15251 adaptive comfort temperatures for selected Canadian cities for the month of July. The ASHRAE upper comfort temperatures vary between 26.1°C (St John's) and 28.2°C (Toronto), whereas for the EN15251 standard they vary between 28.7°C (St John's) and 31°C (Toronto).

Table 8. ASHRAE-55 and EN15251 adaptive comfort temperatures for selected Canadian cities in July. The monthly averages are taken from the historical climate data of 1981-2010 (Source: EC, 2018b;)

Location	July average outdoor temperature (°C)	ASHRAE-55 Lower comfort temperature (°C)	ASHRAE-55 Upper comfort temperature (°C)	EN15251 (III) Upper comfort temperature (°C)
St John's (NF)	15.5	19.1	26.1	28.7
Charlottetown (PEI)	18.7	20.1	27.1	29.8
Halifax (NS)	18.8	20.1	27.1	29.8
Moncton (NB)	19.5	20.3	27.3	30.1
Montreal (QC)	21.2	20.9	27.9	30.6
Ottawa (ON)	21.2	20.9	27.9	30.6
Toronto (ON)	22.3	21.2	28.2	31.0
Winnipeg (MB)	19.7	20.4	27.4	30.1
Saskatoon (SK)	18.5	20.0	27.0	29.7
Calgary (AB)	16.5	19.4	26.4	29.1
Vancouver (BC)	18.0	19.9	26.9	29.6

7.2 PHYSIOLOGICAL METRICS

Physiological heat stress metrics are based on the absolute thresholds of heat stress (e. g., maximum body core (rectal) and skin temperatures, water loss, and other relevant factors) or heat strain (e.g., maximum skin wetness and sweat rate, and other factors), or use the concept of reducing the actual environment and in which the occupant is situated to an imaginary environment having an equivalent temperature in which the imaginary occupant would experience the same thermal sensation, or heat stress and strain as in the actual environment. The metrics, based on the absolute limits for threshold values of physiological stress and strain, can be applied to any environment. However, the metrics that use the concept of equivalent temperature are valid only for the reference environment conditions. The metrics are calculated based on the heat balance of the human body of a

healthy individual, and are therefore the most accurate indices. The human body bioheat models range from a very simple one-node (skin temperature) and two-node (skin and body core temperatures) models to multi-segment and tissue node models. The specific characteristics of individuals (e.g. gender, age, mass, height, basal metabolic rate, clothing, etc.), physiological acclimatization (e.g., vasodilation, vasoconstriction, sweat rate, etc.) and behavioural adaptation (e.g., activity level, clothing) can therefore be taken into account. The simple one or two-node models are suitable for the average comfort of a human body, however excluding thermal discomfort at exposed body parts. The multi-node models are, however, suitable for determining both the average and local thermal comfort. The multi-node models divide the body into various segments (i.e. head, face, neck, thorax, abdomen, body core, body skin, upper/lower arms, upper/lower legs, hand, foot) with suitable models for blood flow and thermal exchange with the environment as derived from laboratory studies. Most of the models are currently available for young adults of an average age of 35 years. There are, however, recent attempts to develop specific bioheat models for the elderly by taking into account the physiological and thermoregulatory changes as occur in the aged (Rida et al., 2014; Ma et al., 2017). The primary influential model parameters for the elderly include: basal metabolic rate, cardiac output, body fat to mass ratio, body core and skin temperature thresholds for vasodilation and vasoconstriction, and skin blood flow and sweat rates.

The range of values for physiological indices are developed based on the absolute values of the physiological heat stress and strain thresholds (body core and skin temperatures, skin wettedness, etc.) or the subjective PMV thermal comfort scale. Most of the indices are used for indoor exposure, some are suitable for outdoor exposure, and others for both indoor and outdoor exposure. Nonetheless there is no proper index scale for the elderly or children (i.e. < 15 years). The commonly used indices include the following:

Perceived Temperature (PT) — PT is designed for outdoor exposure to predict the heat and cold stress on people. It is defined as the equivalent temperature of a reference environment that would result in the same thermal perception as in the actual outdoor environment (Jendritzky et al., 2000). The reference environment is set to have the same relative humidity as outdoors, whereas wind velocity is reduced to a slight draught, and MRT equals the air temperature, in which an average male person wearing summer (0.5 clo) or winter (1.75 clo) clothing is engaged in a walking activity (metabolic rate of 2.3 met) at a speed of 4 km/h. PT uses a linear correlation as a function of the PMV index and the clothing insulation value. The PMV index for outdoors is calculated using the Klima-Michel model, which uses the one-node Fanger PMV bioheat model with modifications to the MRT to account for solar and thermal radiation of the outdoor environment. PT is typically used by the German weather services (Deutscher Wetterdienst; Jendritzky et al., 2000). Table 8 lists the PT thermal sensation scale in accord with the PMV index scale.

Table 9. Thermal sensation scale of the perceived temperature (PT)

PT (°C)	Thermal sensation	Physiological state
Above 38	Very hot	Extreme heat stress
32 to 38	Hot	Heavy heat stress
26 to 32	Warm	Moderate heat stress
20 to 26	Slightly warm	Low heat stress
0 to 20	Comfortable	Comfort possible
0 to -13	Slightly cool	Low cold stress
-13 to -26	Cool	Moderate cold stress
-26 to -39	Cold	Heavy cold stress
Below -39	Very cold	Extreme cold stress

Standard Effective Temperature (SET) — SET is defined as the temperature of an imaginary indoor environment at 50% relative humidity and MRT equals the air temperature, in which an imaginary occupant wearing clothing standardized for activity has the same heat stress (skin temperature) and strain (skin wettedness) as in the actual environment (ASHRAE, 2017). SET is calculated using the two-node bioheat model of Gagge et al. (1986) for indoor exposure. The SET thermal sensation scale is based on the maximum skin temperature and wettedness (Blazejczyk et al., 2012). ASHRAE (2017) adopted SET for the calculation of thermal comfort under higher air speeds than the maximum allowable limit in the PMV model. Recently, the U.S. Green Building Council (USGBC) has adopted SET for Passive Survivability-Thermal Resilience (space overheating) criteria in buildings to earn LEED points (Overbey, 2018). Pickup and de Dear (2000) developed OUTSET for outdoor environments by including the solar and thermal radiation in the definition of MRT. Table 10 lists the SET thermal sensation scale and its corresponding physiological state (Parsons, 2003).

Table 10. Thermal sensation scale of the Standard Effective Temperature (SET)

SET (°C)	Thermal sensation	Physiological state
> 37.5	Very hot, very uncomfortable	Failure of thermoregulation
34.5 - 37.5	Hot, very unacceptable	Profuse sweating
30.0 - 34.5	Warm, uncomfortable, unacceptable	Sweating
25.6 - 30.0	Slightly warm, slightly unacceptable	Slight sweating, vasodilation
22.2 - 25.6	Comfortable and acceptable	Neutrality
17.5 - 22.2	Slightly cool, slightly unacceptable	Vasoconstriction
14.5 - 17.5	Cool and unacceptable	Slow body cooling
10.0 - 14.5	Cold, very unacceptable	Shivering

Universal Thermal Climate Index (UTCI) — UTCI is defined as the equivalent temperature of a reference outdoor environment causing the same physiological response as in the actual environment (Blazejczyk et al., 2013). The reference outdoor conditions are: wind speed of 0.5 m/s measured at 10 m height (corresponding to 0.3 m/s at 1.1 m height), MRT = air temperature, vapor pressure equals 2 kPa (equivalent to 50% relative humidity

at 29°C), in which an average person with a clothing level adapted to the outdoor temperature is walking at a speed of 4 km/h (1.1 m/s), generating a metabolic rate of 135 W/m² (2.3 met). UTCI uses sixth order polynomial regression correlations that link the actual outdoor conditions (temperature, vapor pressure, wind speed, and solar radiation) to the physiological response of an average person. The correlations were developed using the multi-node bioheat model of Fiala et al. (2012) coupled with a complex clothing model (Havenith et al., 2012) for the outdoor environment. The correlations covered a wide range of activity levels up to heavy exercise and thermal conditions that include steady state and transient conditions with cold stress, cool, warm, and hot stress. The Fiala's bioheat model uses 12 body segments with 187 tissue nodes. Table 11 lists the UTCI thermal sensation scale and its corresponding physiological state (Blazejczyk et al., 2013).

Physiologically Equivalent Temperature (PET) — PET is defined as the equivalent temperature of an imaginary indoor environment at a vapor pressure of 1.2 kPa (50% relative humidity at 20°C), air speed of 0.1 m/s, and MRT equals the air temperature, in which an imaginary occupant wearing standard clothing (0.9 clo, typical for office work) in light activity (work metabolism of 80W on top of the basal metabolism, equivalent to 1.5 met) produces the same temperature sensation (body core and skin temperature) as in the actual environment (Höppe, 1999). The PET calculation is based on the Munich energy balance model for individuals (MEMI), which is a two-node model similar to that of Gagge et al. (1986), but with different treatments for skin temperature, sweating and heat transfer from body parts. The PET scale was developed by mapping PET values of the reference thermal conditions to its corresponding PMV scale (Matzarakis and Amelung, 2008). Furthermore, there have so far been no extensive studies undertaken to validate the PET thermal scale for various climatic cases. Lin and Matzarakis (2008) found that a significant difference in the PET thermal sensation scale between Taiwan, and Western and Central Europe. Table 12 lists the PET thermal sensation scale (Matzarakis and Amelung, 2008). PET was recommended in German guidelines developed for urban and regional planners (Matzarakis and Amelung, 2008). The PET bioheat model and solar radiation model for the exterior MRT calculation have been implemented in freeware RayMan software (Matzarakis et al., 2010).

Modified physiologically equivalent temperature (mPET) — mPET is similar to PET but this index uses the Penny's transient multi-node (16 to 26) bioheat model coupled with a multi-layer clothing model (insulation value varying from 0.3 to 2.5 clo depending on air temperature) with vapour diffusion properties (Chen and Matzarakis, 2014). mPET uses the same reference thermal conditions and temperature sensation scale as that of PET. Results derived from mPET for the body core and skin temperatures were more reasonable than those obtained from PET, particularly for the above warm and below cool conditions due to the adaptive clothing model of mPET (Chen and Matzarakis, 2017). However, the mPET thermal sensation scale still requires development.

Table 11. Thermal sensation scale of the UTCI

UTCI (°C)	Thermal sensation	Physiological state
above 46	extreme heat stress	<ul style="list-style-type: none"> • increase in rectal temperature time gradient • steep decrease in total net heat loss • averaged sweat rate >650 g/h, steep increase
38 to 46	very strong heat stress	<ul style="list-style-type: none"> • core to skin temperature gradient < 1°C (at 30 min) • increase in rectal temperature at 30 min
32 to 38	strong heat stress	<ul style="list-style-type: none"> • Dynamic Thermal Sensation (DTS) at 120 min >+2 • averaged sweat rate > 200 g/h • increase in rectal temperature at 120 min • latent heat loss >40 W at 30 min • instantaneous change in skin temperature > 0°C/min
26 to 32	moderate heat stress	<ul style="list-style-type: none"> • change of slopes in sweat rate, rectal temperature and skin temperature: body average, face, and hands • occurrence of sweating at 30 min • steep increase in skin wetness
9 to 26	no thermal stress	<ul style="list-style-type: none"> • averaged sweat rate > 100 g/h • DTS at 120 min < 1 • DTS between -0.5 and +0.5 (averaged value) • latent heat loss >40 W, averaged over time • plateau in rectal temperature time gradient
9 to 0	slight cold stress	<ul style="list-style-type: none"> • DTS at 120 min < -1 • local minimum of hand skin temperature (use gloves)
0 to -13	moderate cold stress	<ul style="list-style-type: none"> • DTS at 120 min < -2 • skin blood flow at 120 min lower than at 30 min (vasoconstriction) • averaged face skin temperature < 15°C (pain) • decrease in hand skin temperature • rectal temperature time gradient < 0°C/h • 30 min face skin temperature < 15°C (pain)
-13 to -27	strong cold stress	<ul style="list-style-type: none"> • averaged face skin temperature < 7°C (numbness) • rectal temperature time gradient < -0.1 K/h • rectal temperature decreases from 30 to 120 min • increase in core to skin temperature gradient
-27 to -40	Very strong cold stress	<ul style="list-style-type: none"> • 120 min face skin temperature < 0°C (frostbite) • steeper decrease in rectal temperature • 30 min face skin temperature < 7°C (numbness) • occurrence of shivering • rectal temperature time gradient < -0.2°C/h • averaged face skin temperature < 0°C (frostbite) • 120 min face skin temperature < -5°C (high risk of frostbite)
below -40	extreme cold stress	<ul style="list-style-type: none"> • rectal temperature time gradient < -0.3°C/h • 30 min face skin temperature < 0°C (frostbite)

Table 12. Thermal sensation scale of the physiologically equivalent temperature (PET)

PET (°C)	Thermal sensation	Physiological state
Above 41	Very hot	Failure of thermoregulation
35 - 41	Hot	Strong heat stress
29 - 35	Warm	Moderate heat stress
23 - 29	Slightly warm	Slight heat stress
18 - 23	Comfortable	No thermal stress
13 - 18	Slightly cool	Slight cold stress
8 - 13	Cool	Moderate cold stress
4 - 8	Cold	Strong cold stress
Below 4	Very cold	Extreme cold stress

7.3 METEOROLOGICAL-BASED METRICS

The meteorological based metrics are derived from empirical studies that combine various weather variables (i.e. temperature, relative humidity, wind speed, solar radiation) in one index that relates to the thermal sensation, physiological response, or purely the overall heat transfer from the human body. The commonly used indices include:

Humidex — The Humidex is a dimensionless index that combines the air temperature and vapour pressure to indicate the perceived temperature of the outdoor environment. It was developed by Canadian meteorologists Masterson and Richardson (1979) and is regularly used by the Canadian weather forecast services to produce heat alert warnings for the general public (EC, 2018c; <https://weather.gc.ca/>), provincial jurisdictions to produce heat alert and response plans (HC, 2012), and occupational health and safety organisations for protecting workers from heat stress (OHCOW, 2018). Table 13 lists the Humidex scale (EC, 2018c). Note that for a typical indoor setting of relative humidity = 50%, wind speed = 0.15 m/s, metabolic rate = 1 met (sedentary activity), and typical summer clothing insulation = 0.5 clo, the Humidex values of = 20, 30, 40, and 45 correspond to operative temperatures of 19.7°C (PPD = 93%), 26°C (PPD = 5%), 32°C (PPD = 84%), 35°C (PPD = 100%), respectively. Humidex values above 29 correspond to ranges of thermal discomfort.

Table 13. Humidex scale and its corresponding thermal comfort scale in terms of operative temperature and PPD for a typical indoor setting of: RH = 50%, wind speed = 0.15 m/s, metabolic rate = 1 met (sedentary activity), and summer clothing insulation = 0.5 clo.

Humidex	Thermal sensation	Equivalent operative temperature and PPD
20 - 29	Comfortable	19.7°C (PPD = 93%) - 25.5°C (PPD = 5%)
30 - 39	Some discomfort	26°C (PPD = 7%) - 31.5°C (PPD = 76%)
40 - 45	Great discomfort; avoid exertion	32°C (PPD = 93%) - 35°C (PPD = 100%)
Above 45	Dangerous; heat stroke possible	> 35°C (PPD = 100%)

Heat Index (HI) — HI is similar to the Humidex. It is a simple relationship that combines the air temperature and relative humidity to indicate the perceived temperature of the outdoor environment (Rothfus, 1990). It is expressed in temperature units (°C, or °F), and was originally derived through regression analysis based on the physiological based apparent temperature (AT) concept of Steadman's (1979). HI is widely used by the National weather services of the United States of America (NOAA, 2018).

Table 14 lists the HI scale (NOAA, 2018) and its corresponding thermal comfort index for a typical summer indoor setting (relative humidity = 50%, wind speed = 0.15 m/s, metabolic rate = 1 met (sedentary activity), and summer clothing insulation = 0.5 clo). The HI range (i.e. 27 – 32) of values encompass the comfort regions related to neutral, slightly warm, and warm conditions.

Table 14. Heat Index scale and its corresponding thermal comfort scale in terms of operative temperature and PPD for a typical indoor setting of: RH = 50%, wind speed = 0.15 m/s, metabolic rate = 1 met (sedentary activity), and summer clothing insulation = 0.5 clo

HI (°C)	Thermal sensation	Equivalent operative temperature and PPD
27–32	Caution	27°C (PPD = 7%) – 30.5°C (PPD = 57%)
32–41	Extreme Caution	30.5°C (PPD = 57%) - 35°C (PPD = 100%)
41–54	Danger	35°C (PPD = 100%) - 40°C (PPD = 100%)
Above 54	Extreme danger	> 40°C (PPD = 100%)

Wet-Bulb Globe Temperature (WBGT) — WBGT is a simplified version of the empirically derived Corrected Effective Temperature (CET) scale (Parsons, 2003; 2006). It was originally developed for the US Navy for military training in hot environments to avoid heat related injuries (Blazejczyk et al., 2012; Parsons, 2006). Currently, WBGT is by far the most widely used occupational heat stress index in the world. It has been adopted by the National Institute for Occupational Safety and Health (NIOSH, 1986) and is referenced in the ISO 7243 standard for workplace ergonomics of the thermal environment (ISO, 2017). WBGT combines the weather variables (i.e. air temperature, relative humidity, wind speed, and solar and thermal radiation) in a linear weighting sum of the air, black globe, and naturally ventilated web bulb temperatures. Two equations are produced for healthy and physically fit people wearing reference clothing (i.e. long sleeve cotton shirt and pant with a solar absorptivity of 0.67 and insulation value of 0.6 clo) and working in either indoor or outdoor environments (ISO, 2017; Parsons, 2006). For indoor exposure, the air temperature is made equal to the black globe temperature (or MRT = ambient air temperature). The American Conference of Government Industrial Hygienists (ACGIH) published the Permissible heat exposure Threshold Limit Values (TLVs) that correspond to thermal conditions in which the body core (rectal) temperature does not exceed 38°C for a sustained exposure of up to 8 hours (working day). Some Canadian jurisdictions have adopted these TLVs as occupational exposure limits and other use them as guidelines (CCOHS, 2018). For clothing insulation different than the reference clothing, a clothing adjustment value is made to the reference values of WBGT. There is, however, no adjustment made to account for gender, body size or height. Table 15 list the TLV reference values of the WBGT for acclimatized and un-

acclimatized persons according to the ISO 7243 standard (ISO, 2017). The corresponding operative (or air) temperatures under typical indoor conditions (MRT = air temperature, relative humidity = 50% and air speed = 0.15m/s) are also included in the table for comparison purposes (calculation of the operative temperature, T_{op} , was done using the WBGT 2.1 computer tool (Wasmer, 2008)). The WBGT threshold limits are several degrees higher than the adaptive thermal comfort limits (Table 7). The preferred calculation of WBGT is based on the direct measurement using special apparatus and sensors for the naturally ventilated wet bulb and black globe temperatures (ISO, 2017). Different analytical models to compute WBGT using the weather variables as inputs have also been proposed (ISO, 2017; Kjellstrom et al., 2009), but the most recent model by Liljegren et al. (2008) seems the most accurate one with an accuracy lower than 1°C.

Table 15. TLV reference values of the WBGT and its corresponding operative temperatures under typical indoor conditions for acclimatized and un-acclimatized persons with reference clothing (ISO, 2017). Clothing adjustment to WBGT may be found in ISO (2017) and Havenith and Fiala (2016).

Metabolic rate classes	Metabolic rate (W)	Acclimatized persons		Un-acclimatized persons	
		WBGT (°C)	T_{op} (°C)	WBGT (°C)	T_{op} (°C)
Resting	115	33	39.4	32	38.4
Low (light work)	180	30	36.2	29	35.2
Moderate (medium work)	300	28	34.1	26	31.9
High (intense work)	415	26	31.9	23	28.7
Very high (very intense work)	520	25	30.9	20	25.5

7.4 EPIDEMIOLOGICAL METRICS

Epidemiological metrics are based on mortality and morbidity data due to heat. Chen and Berry (2013) have listed more than 20 epidemiological metrics. The most commonly used epidemiological metrics include excess daily all-cause mortality, excess daily non-accidental mortality, and excess daily cause-specific mortality. Mortality counts for a specific location are collected over a period of time (several years) and statistically analysed as a function of the outdoor weather or weather-based variables to establish mortality profiles for the selected location (e.g. see Figure 4). The thresholds of the weather or weather-based predictors that indicate the departure of the mortality data from the reference value and its slope are established and used by health authorities in the community's heat alert and response systems (HARS) to protect public health under extreme heat events. Among the weather predictors that correlate well with the excess daily mortality include the daily average temperature, the daily maximum temperature, the daily minimum temperature, or the combination of the daily maximum and minimum temperatures. Other weather-based predictors such as the humidex, heat index, apparent temperature, and perceived temperature have also been used for the mortality profiles (Barnett et al., 2010). It should be noted that in general, epidemiological metrics are not accurate due to many confounding factors such as the prevailing climate at the location, the presence of air pollution, socio-economic status of population, and other relevant factors. Therefore, these metrics vary from location to location. Furthermore, the metrics are not directly linked to the actual exposure due to heat island effects or indoor conditions of the built

environment where people spend most of their time. However, the metrics are useful when they are used for specific communities to alert the public to extreme heat events.

A comparison of the strengths and weaknesses of some commonly used heat stress indices is given in Table 16 .

Blazejczyk et al. (2012) compared some selected indices with the Universal Thermal Climate Index (UTCI) for outdoor exposure. The selected indices include heat index (HI), humidex, Effective Temperature (ET), Apparent Temperature (AP), Perceived Temperature (PT), simplified version of the WBGT for indoor, SET, and PET. SET was found the best metric to correlate with UTCI, followed by PT, and PET. The HI, WBGT-indoor, and humidex were found weakly correlated to UTCI due to the fact that these indices do not account for wind speed and solar radiation. Chindapol et al. (2017) compared several heat stress indices for the elderly located in tropical climates. Five physiologically based heat stress indices (UTCI, WBGT, Tropical Summer Index (TSI), Heat Stress Index (HSI), and Discomfort Index (DI) were compared with the perception (subjective) based indices (Thermal Sensation Vote, TSV) under indoor exposure using survey data collected in low-income residential buildings. HSI was found to be the best index to correlate with TSV for the elderly in hot climates.

Table 16. Strengths and weaknesses of some commonly used heat stress metrics.

Heat stress metric	Strengths	Weaknesses
Thermal comfort based		
PMV-PPD	<ul style="list-style-type: none"> • Uses a simple (one node) heat balance model • Suitable for indoor environment • Indicates average comfort • Universally used for air conditioned buildings • Adopted by many international standards (e.g., ASHRAE 55-2017; EN15251-2007) • Easy to implement in calculation programs 	<ul style="list-style-type: none"> • Not suitable for outdoor environment • Perception based heat stress index • Local body discomfort not accounted for • Not applicable for non-air conditioned buildings • Does not account for people acclimatization
Adaptive thermal comfort	<ul style="list-style-type: none"> • Suitable for indoor environment • Indicates average thermal comfort • Predicts only neutral temperature conditions • Widely used in naturally ventilated or free-running buildings • Accounts for people adaptation • Adopted by many international standards (e.g., ASHRAE 55-2017; EN15251-2007) • Easy to implement in calculation programs 	<ul style="list-style-type: none"> • Not suitable for outdoor environment • Applicable only for warm outdoor environments ($10\text{ }^{\circ}\text{C} \leq T \leq 33.5\text{ }^{\circ}\text{C}$) • Valid for light activity levels (1 to 1.3 met) • Does not explicitly account for the effect of varying indoor temperature, relative humidity, and air speed • Temperature thresholds change from month to month (or week to week), makes it difficult to interpret performance results • EN15251 needs at least a week of continuous temperature measurement • It is not a heat stress index
Physiological-based		
Perceived temperature (PT)	<ul style="list-style-type: none"> • Version of PMV for outdoor environment • Accounts for all weather variables • Indicates average comfort • Used in German weather services (Jendritzky et al., 2000) 	<ul style="list-style-type: none"> • Not applicable to indoor environment • Perception based heat stress index • Valid for the reference conditions • Does not account for people acclimatization (Kim et al., 2009)
Standard effective temperature (SET)	<ul style="list-style-type: none"> • Uses a two-node heat balance model • Suitable for indoor environment 	<ul style="list-style-type: none"> • The outdoor version is not widely used • Local body discomfort not accounted

Heat stress metric	Strengths	Weaknesses
	<ul style="list-style-type: none"> Indicates average comfort Version for outdoor environment is available (OUTSET) Accounts for all weather variables Thermal scale based on physiological heat stress and strain Adopted in ASHRAE 55-2017 standard Easy to implement in calculation programs 	<ul style="list-style-type: none"> Valid for the reference conditions Does not account for people acclimatization
Universal Thermal Climate Index (UTCI)	<ul style="list-style-type: none"> Uses a multi node heat balance model Developed for outdoor environment Accounts for all weather variables Accounts for people behavioural adaptation through the adaptive clothing model Thermal scale is based on physiological heat stress and strain Accounts for average and local body comfort Uses simple correlations, easy to implement in calculation programs Accounts for transient conditions 	<ul style="list-style-type: none"> Not applicable to indoor environment Not valid out of the correlation variable ranges Valid for the reference conditions Does not account for people acclimatization
Physiologically equivalent temperature (PET)	<ul style="list-style-type: none"> Uses a two-node heat balance model Developed for outdoor environment Accounts for all weather variables Account for the average comfort Recommended in the German guidelines for urban and regional planners 	<ul style="list-style-type: none"> Not applicable to indoor environment Uses the PMV comfort scale. Needs further validation studies for generalisation to various climates Valid for the reference conditions Does not account for people acclimatization
Modified physiologically equivalent temperature (mPET)	<ul style="list-style-type: none"> Uses a multi-node heat balance model Developed for outdoor environments Accounts for all weather variables Accounts for people behavioural adaptation through the adaptive clothing model Account for average and local body comfort Accounts for transient conditions 	<ul style="list-style-type: none"> New index Uses the PMV comfort scale. Needs further validation studies for generalisation to various climates Valid for the reference conditions Does not account for people acclimatization
Meteorological-based		
Humidex	<ul style="list-style-type: none"> Empirically based Suitable for outdoor environments but it can be applied to indoor environments Regularly used in Canadian weather services Simple and easy to implement in calculation programs 	<ul style="list-style-type: none"> Indicates perceived temperature due to heat and moisture only Does not account for other weather variables such as wind and solar radiation Not directly related to heat stress
Heat index	<ul style="list-style-type: none"> Empirically based Suitable for outdoor environments but it can be applied to indoor environments Regularly used in USA weather services Simple and easy to implement in calculation programs 	<ul style="list-style-type: none"> Indicates perceived temperature due to heat and moisture Does not account for other weather variables such as wind and solar radiation Not directly related to heat stress
Wet-bulb-globe-temperature (WBGT)	<ul style="list-style-type: none"> Physiologically derived metric Used for indoor or outdoor environments Accounts for all weather variables Widely used in standards for occupational health and safety and workplace ergonomics 	<ul style="list-style-type: none"> Difficult to measure Needs expensive equipment Applicable to hot environments only Needs further adjustment for protective clothing (Havenith and Fiala, 2016)
Epidemiological based		

Heat stress metric	Strengths	Weaknesses
Excess daily mortality	<ul style="list-style-type: none"> Indicates direct heat-related health outcomes of a community Uses simple and familiar weather predictors (max/min/average daily temperature) that can be monitored on a daily basis Used in some community's heat alert and response systems for the public health protection 	<ul style="list-style-type: none"> Has a lot confounding factors Has long time lag periods (days to weeks) Dependent on location and population Lack of mortality data for some communities Uses the outdoor environment as predictors, it does not therefore account for indoor exposure or urban heat islands Needs extensive statistical analysis for the metric development

8. OVERHEATING IN BUILDINGS

It is evident that summertime extreme heat events as may arise from climate change are a potential threat to the comfort and health of people in urban areas. Buildings may play a major role to limit such effects and protect occupants from the harmful outside environment (Loughnan et al., 2015; van Loenhout et al., 2016). Buildings influence the indoor thermal conditions to which people (occupants) are exposed most of the time and experience the imposed thermal stresses. Vulnerable buildings which house vulnerable people or buildings with poor management of the indoor thermal conditions will suffer the most from the effects of EHEs. The indoor conditions are direct consequences of the outdoor conditions, but the severity of the indoor conditions depends on many other factors, among which are building type (houses and retirement homes, apartment buildings, schools, hospitals, etc.), internal space usage (occupant density, internal heat gains), construction characteristics (insulation levels, window proportions, solar shading, orientation of facades), and building operation (air-conditioning use, natural ventilation, etc.) (Quinn et al., 2014). Due to such confounding factors, the effects of the indoor thermal conditions on the health of people are not widely known as relates to the outdoor conditions so that appropriate threshold temperatures for indoor space overheating can be developed for particular building types.

8.1 FIELD MEASUREMENT STUDIES

There have been many studies undertaken around the globe where field measurements in various types of buildings have been obtained in support of establishing a relationship between indoor and outdoor conditions. Mavrogianni et al. (2010) selected 36 dwellings for monitoring studies of space overheating in the urban heat island of London (UK) during the mild summer of 2009. The study used the CIBSE guide A (CIBSE, 2006) for classification of indoor spaces for overheating. Based on the thermal comfort limits, the temperature thresholds of 28°C and 26°C were used for living rooms and bedrooms, respectively. Overheating was declared when the indoor temperature exceeded such thresholds for 1% of the annual occupied hours. The study found that 42% of the monitored dwellings failed the nighttime overheating criteria, particularly for apartment flats.

White-Newsome et al. (2012) conducted a field measurement study during the cool summer of 2009 in 30 old homes and flats occupied by the elderly in Detroit, Michigan. About 50% of the houses had air conditioning. The study found that the average maximum indoor temperature was 34.85°C, which was 13.8°C higher than the average maximum outdoor temperature. Houses with PVC and wood claddings were more sensitive than brick homes to changes in outdoor temperature. The indoor temperature was found dependent on the outdoor temperature, solar radiation, and dew point temperature.

Beizaee et al. (2013) conducted a national scale field measurement study during the cool summer of 2007 in 207 dwellings across England, UK. Among the dwellings, 193 were free-running (not air-conditioned). The adaptive thermal comfort thresholds provided in the BS/EN15251 standard were used for classification of space overheating. The study found that despite the cool summer, 21% of the bedrooms had more than 5% of nighttime hours over the upper limit temperature (26°C) for bedrooms. Bedrooms of homes built after 1990 were significantly warmer, particularly those of apartment flats, and those built before 1919 were significantly cooler. This raises a concern that new and highly insulated dwellings are more prone to overheating than older homes.

Montazami and Nicol (2013) conducted a field measurement and occupant survey study for 140 classrooms in 18 naturally ventilated primary schools in London (UK) during the summer months of June and July of 2005, 2007, and 2008. The field data was used to compare the old and new overheating criteria of the UK Department of Education and Skills (DfES). The old overheating criteria of DfES used the fixed temperature exceedance threshold of 28°C whereas the new ones are based on the adaptive thermal comfort described in EN15251-2007 (CEN, 2007). The results indicated that the new guidelines for the DfES were more stringent than the old one and are therefore better in avoiding overheating in schools. The authors suggested using the maximum temperature of building category I (for sensitive occupants) instead of II (new built) since students were found to be more sensitive to thermal discomfort, and as such, the exceedance time prescribed in the standard of 3% ought to in fact to be 1%.

Quinn et al. (2014) conducted a field measurement study during the summer of 2003 to 2011 in 285 low and middle-income homes in New York City NYC, USA. Information on the use of air conditioning was not collected, but city surveys indicated that 12.5% of adults did not use air conditioning in their homes. The intent of the measurement was to develop a linear relationship between the indoor and outdoor conditions so that it could subsequently be applied to the heat waves of 2006 in NYC and 2003 in Paris, France. The heat index was used as a measure of heat-related health. The measurement indicated that there was a direct link between the indoor and outdoor conditions, but the indoor heat index metric showed a significant variability among the homes studied. It was found that the respective construction characteristics of the buildings and as well how occupants managed the indoor environment posed an additional risk to vulnerable people during extreme heat events.

Loughnan et al. (2015) conducted field measurements and occupant surveys in 20 air-conditioned houses of a group of elderly living in a rural regional town in Australia during the summer of 2012. The daily mean,

maximum, and minimum outdoor temperatures over the study period were 27.8°C, 37.5°C, and 14.4°C respectively. The study found that the indoor maximum temperature was not significantly correlated with the outdoor temperature. The residents reported comfortable feelings for temperatures up to 26.6°C. Significant differences in the indoor temperature were related to the house characteristics and operation. Brick veneer houses showed smaller changes in the diurnal temperature compared to other houses.

Van Loenhout et al. (2016) conducted surveys and field measurements in 113 homes for the elderly in Netherlands in the summer of 2012. The study found that the indoor temperature varied among the homes, and was strongly related to the reported heat-related health problems of the elderly. During the warmest week of the study period with, respectively, the daily mean, maximum and minimum outdoor temperatures of 23.6°C, 24.7°C, and 22.7°C, the temperatures of living rooms and bedrooms were higher than outdoors, and varied from 20.8°C to 30.2°C despite the use of air conditioning. More than half of the respondents perceived their indoor spaces as too warm, and the most reported symptoms were thirst (42.5%), sleep disturbance (40.6%), and excessive sweating (39.6%).

Touchie et al. (2016) conducted field measurements and occupant surveys to evaluate overheating in post-war multi-unit residential buildings in Toronto, Canada. The study was part of a program to retrofit buildings to reduce city GHG emissions. Pre and post-retrofit measurements were taken for one year in 65 suites of seven buildings. The pre-retrofit survey data were collected over 10 days between the months of January and February of 2015. About 47% of the monitored suites had free-standing or window-mounted air-conditioner units, and some residents had free-standing fans. The overheating was evaluated in terms temperature exceedance over the static thermal comfort thresholds of 24°C, 26°C and 28°C. The measurements indicated that chronic overheating was present in all buildings during the summer months that were monitored with an average suite temperature of 27.7°C and maximum temperature over 34°C. During the heat alert for the city, about 80% of suites surpassed 30°C. The data analysis revealed that all suites of all buildings exceeded 24°C and 26°C for 100% and 50% of the summer time, respectively, and some buildings exceeded 28°C for 70 to 80% for the months of June and July. The study concluded that the fixed temperature thresholds were not sufficient to ensure thermal comfort given the large occupant survey response data.

Vellei et al. (2017) conducted surveys and collected temperature and air quality data over two years (2014-2015) for vulnerable and non-vulnerable occupants of homes located in Exeter, UK, where overheating is not common. The study covered 55 newly renovated low-rise social dwellings. The analysis of the thermal comfort responses indicated that vulnerable occupants (i.e. seniors, disabled, and those with long term illnesses) felt cooler compared to non-vulnerable occupants. The study found that overheating according to the CIBSE Guide A criteria (CIBSE, 2015) was found to occur, particularly in homes having vulnerable occupants.

Baborska et al. (2017) conducted a field monitoring study to assess the overheating risk in apartments retrofitted to the current energy efficiency standard in the UK. In the UK apartment flats are known to present a summer overheating issue. The study focused on the home-use practices in relation to the space overheating in 18 apartments of one block tower located in northern England. During the hottest summer

months of July and August, the average indoor temperature was 8°C higher than the outdoor temperature. The temperature measurement showed that overheating occurred in 44% of bedrooms and 28% of living rooms according to the CIBSE's fixed temperature overheating criterion (i.e. 1% of occupied hours above 26°C in bedrooms and 28°C in living rooms). Similar results were obtained using the overheating criterion based on the adaptive thermal comfort given in the BS/EN 15251 standard.

Pathan et al. (2017) conducted occupant surveys and field measurements to assess overheating in 122 dwellings (mainly old houses and flats) in London (UK) in the summer of 2009 and 2010. The occupants of the dwellings were mainly students and university staff. No information was provided on the use of air conditioning. The overheating analysis was conducted using two criteria based on information provided in the CIBSE Guide A static thermal comfort (CIBSE, 2006), and ASHRAE Standard 55 adaptive thermal comfort (ASHRAE, 2017). The study found that the London dwellings faced a significant risk of overheating under the current climate. More than 29% of the living rooms and 31% of the bedrooms exceeded the overheating criteria.

Lomas and Porritt (2017) have recently reviewed literature on overheating in buildings around the world. Different criteria of overheating were presented and analysed. The authors raised some valuable questions on the suitability of the current overheating criteria and highlighted the practical difficulty of applying them in real occupied buildings.

8.2 COMPUTER SIMULATION STUDIES

Similarly, there have been many simulation studies to predict the relationships between indoor and outdoor conditions for buildings under the current and future projected climates. Coley and Kershaw (2010) conducted a parametric simulation study for residential and commercial buildings (houses, apartments, schools, offices) in London (UK) using the IES software. Over 400 combinations of future weather data, building constructions, windows, and ventilation types and strategies were studied. The future weather data were developed based on the UKCP02 climate projection data (monthly averages) for two future scenarios of climate change and the morphing method to convert the monthly averages to hourly weather data. The study found that the indoor temperature is linearly proportional to the outdoor temperature. The proportionality constant is termed "climate change amplification factor", which varies with the building type and the climate change scenario.

Jenkins et al. (2014), Banfill et al. (2013), and Patidar et al. (2014) developed a probabilistic tool to assess the risk of overheating in standard naturally ventilated homes and primary schools in London (UK) under future climate change scenarios. One hundred (100) random weather data were generated for each of three future climate scenarios based the UKCP05 projected climate data. The study used ESP-r software for the simulation. Using statistical techniques, the simulation temperature outputs were analysed from which was developed a linear regression between indoor temperature and outdoor conditions for each building type and adaptation strategy. Based on a given overheating criterion (i.e., temperature thresholds), the regression generated a probabilistic risk for overheating that might occur using the 100 random climate data for each climate scenario.

Patidar et al. (2014) applied this regression to study various criteria for overheating in houses under extreme heat wave events.

Gupta et al. (2015) used the IES software to conduct a simulation study to predict the risk of the projected overheating in 2050 of twelve suburban housing archetypes located in the UK. Driven by the fact that passive cooling may not be sufficient in future climates, the study investigated the energy and emission effectiveness of mechanical cooling technologies to adapt the buildings to the expected warming climate of the future. Probabilistic future weather year datasets (low spatial resolution of 5 km) from UK climate projections (UKCP09) were used. Three (3) house construction types were considered for old, retrofitted and new zero-carbon buildings. All the homes had south facing windows. The overheating criteria given in CIBSE TM52 (CIBSE, 2013) and based on the adaptive thermal comfort, were used for the analysis. Four (4) cooling technologies were assessed including ceiling fans, heat pumps, and standard as well as solar air-conditioning (solar absorption chiller). The study found that for retrofits, the heating demand is projected to remain dominant whereas for the new-builds greater cooling system efficiency will be required. The heat recovery element in the mechanical ventilation systems may be rendered unnecessary in super-efficient homes. Ceiling fans coupled with natural ventilation may be sufficient in providing thermal comfort in the north of England.

Dodoo and Gustavsson (2016) carried out a simulation study using VIP+ software to investigate the effects of future climate change on energy performance, peak loads and overheating risk in three types of apartment buildings located in Sweden having prefabricated concrete, massive timber or light timber structures. The buildings were simulated using the historical TMY weather data of 1961-1990, and 1996-2005, and the projected weather data for 2050-2059 and 2090-2099. The morphing method was used to generate the future hourly weather data from the projected monthly average regional climate data for two climate scenarios (RCP4.5 and RCP8.5). The thermal comfort based overheating criteria of the CIBSE Guide A (CIBSE, 2006) was used for the analysis. The study found the cooling loads and risk of overheating increased considerably for the future climate scenarios considered. Overheating risk was found to be slightly greater for massive-frame buildings and slightly lower for light-frame buildings.

Invidiata and Ghisi (2016) carried out a simulation study using EnergyPlus software to investigate the effects of future climate change on energy performance and thermal comfort in a single family homes located in three Brazilian cities. The world weather file generator (Jentsch et al., 2008) was used to produce the hourly weather data for future typical years of 2020, 2050 and 2080 of the A2 medium emission scenario. The adaptive thermal comfort of the ASHRAE 55 standard (ASHRAE, 2017) was used when the house was set under the natural ventilation strategy. The study found that the use of passive solar design may reduce by up to 50% the future annual cooling and heating energy use in such homes.

Simson et al. (2017) carried out field measurements in 16 apartment buildings and simulations in 25 new apartment buildings in Estonia to verify the compliance with the new government regulation for space overheating. The buildings were multi-storey with massive concrete structures and naturally ventilated. The simulation used the IDA-ICE software and TMY weather data. The overheating risk was assessed in terms of

the number of degree hours (DH) exceeding a baseline temperature of 27°C during the summer period from June to August. Overheating was declared when DHs exceeded 150 Kh. The measurement showed out that the indoor temperatures rose to 32°C and the majority of the dwellings experienced temperatures higher than 27°C. Similarly, the simulation results showed that 68% of the new buildings did not meet the requirements of the new overheating regulation.

Symonds et al. (2017) studied the risk of overheating in English dwellings by comparing field measurements with results from simulation. The measurements were taken in 823 representative dwellings in the summer of 2011. The dwellings that were monitored were simulated using EnergyPlus software. Due to the lack of information on the dwelling characteristics, the simulation results were not in good agreement with the measurements. The simulation results did, however, provide an improved estimate of indoor temperatures when aggregated over dwellings within a particular region.

8.3 ADAPTATION MEASURES

The expected warming of the climate in the future has prompted many researchers to investigate the effectiveness of some adaptation measures to reduce overheating of the indoor space and energy use in various building types for both old and current construction. Lim et al. (2011) investigated a number of adaptation measures to retrofit a real multi-functional post-secondary school building in London (UK). The building had a mixture spaces with mechanical cooling (30 spaces) and natural ventilation (48 spaces). A simulation model of the building was developed and calibrated against the metered annual energy data. The retrofit measures included upgrading windows from single to double low-e glazing, highly efficient lighting and office IT equipment, and use of thermal mass and night time ventilation. The weather files for future climate years representing “high emission” scenarios for central London were created based on the 50 percentile of the projected UKCP09 climate data for 2050 and 2080. For naturally ventilated spaces, the overheating criterion was based on the CIBSE’s fixed threshold temperature of 28°C for more than 1% of the occupied period. Whereas for mechanically cooled spaces the overheating criterion was based on the exceedance of temperature above the cooling set point of 22°C. The results for naturally ventilated spaces showed some level of mitigation of overheating but the overheating risk was still present for the retrofitted building. For mechanical cooled spaces it was proposed that the cooling set point be raised from 22°C to 27°C to offset the increased cooling demand and energy use.

Porritt et al. (2012) conducted a simulation study to rank the effectiveness of several interventions to reduce dwelling overheating during heat waves. The simulated buildings included typical and mid-terrace houses with four orientations and two occupancy profiles. The interventions included insulation renovation added to existing walls and lofts, solar control (i.e. triple glazed low-e windows, reflective internal blinds, overhangs, external shutters, reflective walls and roofs) and ventilation (i.e. night time ventilation, opening windows according to a fixed ventilation schedule). EnergyPlus software and the 2003 heat wave year in London (UK) were used for the simulation. During this heat wave year the measured indoor temperature in dwellings was about 2.3°C

higher than the outdoor temperature with a peak indoor temperature in an apartment room reaching 39.2°C. The overheating criterion used temperature thresholds of 26°C for bedrooms and 28°C for living rooms during the nine day heat wave period. The study found that external insulation and reflective coatings added to existing walls were very effective in reducing overheating, whereas internal wall insulation was less effective and in some cases can increase overheating. The solar shading of windows was found effective particularly for the windows facing south, east and west. Controlled ventilation to prevent hotter outdoor air entering the indoor space was also found to be effective in reducing overheating.

Tillson et al. (2013) investigated several adaptation measures to assess the impact of summertime overheating in the English housing stock. The study used the Standard Assessment Procedure (SAP), which is the UK Government's approved methodology for assessing the energy ratings of dwellings. The SAP is a simple static monthly average simulation tool and its outputs include the monthly average temperatures. SAP predicts that 41% of the housing stock is at a medium to high risk of overheating under the current climate. If summer temperatures increases by 1.4°C under the future climate, then 99% of the housing stock could be at medium to high risk of overheating. Several adaptation measures were therefore investigated including: natural ventilation (i.e. fixed air changes per hour based on the number of storeys, window opening and cross ventilation options in the home); exterior shutters; overhangs; interior curtain and blinds, and; thermal mass. The results showed that under the current climate the ventilation strategies had the largest positive effects, followed by the use of solar shading devices and shutters. For future climates, the solar shading strategies could reduce the risk of overheating by 6%, despite that some dwellings could still be at risk of overheating.

Han et al. (2013) investigated the effectiveness of residential wall retrofits to reduce the overheating risk under heat waves in Melbourne, Australia. Eight residential wall constructions were studied including, insulated double brickwork, un-insulated double brickwork, un-insulated single brickwork, aerated autoclave concrete block, hollow concrete block, regular and deeper width concrete, and timber charwood. A simple one-dimensional heat transfer model was developed for a building with one thermal zone. The weather data used was the 2009 heat wave year. Various criteria were used to assess the wall systems during the heat wave period, including the average maximum air temperature, maximum air temperature difference, thermal discomfort proportion, and statistical maximum air temperature. The results showed that the commonly used un-insulated single brickwork wall was the most vulnerable to heat waves resulting in more than 31.5% of discomfort. The insulated double brickwork system was the most resilient system.

Ascione et al. (2015) investigated the effectiveness of motorized external reflective solar shadings of windows to reduce the overheating risk in a new-build well-insulated office building in Berlin, Germany. The study used EnergyPlus software and the current (average) climate. The building was naturally ventilated and the overheating risk was assessed using the adaptive thermal comfort criteria given in the EN15251 standard. The results showed that the solar shading devices reduced the indoor temperature by 4°C to 6°C for east facing rooms and 3°C to 5°C for west facing rooms.

Vardoulakis et al. (2015) reviewed literature on the effects of climate change on the health of building occupants and the effectiveness of adaptation measures to reduce the risk of overheating in UK residential buildings. The indoor variables that may affect the health of occupants included the temperature, air quality, and allergen and infections. The reviewed measures for adaptation included external solar shading devices, green roofs, reflected envelopes, external wall insulation, roof insulation, opening of windows, and the use of ceiling fans and night time ventilation. The review found that naturally ventilated and super insulated dwellings in London may not meet the thermal comfort target for future years without the use of mechanical cooling. Apartment buildings were generally the warmest and detached houses the coolest. Top floors of flats are considerably more vulnerable to overheating. Newly constructed houses with high insulation levels have the potential to be at a higher risk of overheating than older houses. Mulville and Stravoravdis (2016) investigated the impact of the current regulations to reduce energy use in buildings on the overheating risk of typical dwellings in UK. Five construction standards for dwellings were considered, including the regulatory minimums of Part L 2006 and 2010, voluntary standards of the Code for Sustainable Homes, and the Passive House standard. Typical archetype dwelling models were developed for the housing stock across the UK. The dynamic Heat Transfer in Building 2 (HTB2) software was used for the simulation using the TRY and DSY weather files, which were generated for the current climate and the 50 percentile of the future UKCP09 projections. The overheating risk for free-running houses was assessed in terms of a single temperature exceedance (i.e. 1% of occupied hours above 25°C or 28°C) and adaptive thermal comfort. The study found that the current regulatory requirement to reduce energy use in buildings could result in significant risk of overheating in the near future.

Pyrgou et al. (2017) investigated the effects of building envelope insulation levels on the indoor thermal comfort and cooling energy use of residential buildings under summer heat waves in an urban area in Italy. Two low and high insulation levels were considered for four representative single family detached houses having high mass concrete block walls. EnergyPlus software and the 2013 heat wave weather data (on-site measurement) were used for the simulation. The houses were set in both no cooling and cooling modes. The measured maximum outdoor temperature for the summer period reached 37.3°C and over 30°C for 30.6% of the time during the 26 days of extreme heat. The overheating criteria used the thermal comfort metric. The results showed that the insulated buildings had higher overheating risk and required three times more cooling energy than the traditional non-insulated buildings under extreme heat events. High insulation levels lead to more frequent temperature registration above 26°C whereas active cooling resulted in temperatures between 24°C to 28°C.

8.4 REFERENCE SUMMER WEATHER YEAR FOR ESTIMATING THE RISK TO OVERHEATING

Typical Meteorological Year weather data (TMY) or Test Reference Year (TRY) data for energy calculations are not suitable for carrying out overheating simulation studies given that TMY or TRY data are climate averages over a long period of time (20 to 30 years) and therefore extreme heat events that may occur during such periods of time are likely to be smoothed out. Overheating simulation studies therefore need a reference summer weather year that captures extreme heat events for both historical and future climates. The Chartered

Institution for Building Services Engineers (CIBSE) developed the Design Summer Year (DSY) for overheating analysis of naturally ventilated buildings (CIBSE, 2002). DSY represents a warmer summer than the climatic average, and is defined as the third hottest summer of the 21 year climate data set (i.e. equivalent to a return period of 7 years) in terms of the daily mean dry bulb temperature from April to September (Levermore and Parkinson, 2006). The CIBSE's DSY method assumes the indoor operative temperature is equal to the outdoor temperature. In other words this assumption is equivalent to a conceptual building where occupants are exposed to outdoor conditions, but does not account for the effects of solar radiation, relative humidity and wind. This assumption therefore permits the use of indoor thermal comfort or heat stress metrics to assess the risk of overheating. DSY for the future climate years are obtained using the CIBSE's morphing methodology which converts the projected monthly averages of the climate variables into hourly quantities which are then used to adjust the historical DSY data (Belcher et al., 2005; Jentsch et al., 2008). Since its inception, the DSY methodology has gone through a series of modifications due to the fact that the original DSY method was based on a single weather variable (daily average temperature) to classify heat events. Furthermore, studies in some sites found out that DSY under-predicted the overheating risk (Jentsch et al., 2013). In addition, DSY failed to reproduce some historical extreme heat events such as the 2003 heat wave in Europe (Kershaw et al., 2010). Recently, Eames (2016) has proposed three variants of probabilistic design summer year (pDSY) based on an updated historical climate data set (1984-2013) and the return periods of the heat events. Three classifications of heat events were used and analysed for UK regions to produce these pDSY. The first classification is based on the Weighted Cooling Degree Hours (WCDH). WCDH is a quadratic sum of the operative temperature deviation from the adaptive thermal comfort temperature of the BSEN15251 standard over the summer period. The second classification is similar to the first but uses the Static Weighted Cooling Degree Hours (SWCDH) in which a static threshold temperature is used instead of the adaptive thermal comfort temperature. The static threshold temperature is calculated as the 93 percentile temperature of the region under consideration. The third classification uses the Threshold Weighted Cooling Degree Hours (TWCDH), which combines both WCDH and SWCDH. The generalized extreme value distribution technique was used to calculate the return period of hot summer events. The three summer design years were established as: pDSY-1 - moderate warm year defined as a year with a SWCDH return period close to 7 years; pDSY-2- intense extreme year chosen as the year with the same length of heat events as pDSY-1 but with a higher event intensity; and pDSY-3- long extreme year defined as a more intense year than pDSY-1 but with a longer heat event duration. These pDSY have been adopted in CIBSE TM49 (CIBSE, 2014). More recently, Liu et al. (2016) have reviewed other alternatives to the original definition of DSY, including the near extreme summer reference year (SRY) by Jentsch et al. (2015), and the probabilistic design summer years (pDSY) by Eames (2016). Liu et al. (2016) have also proposed two new alternatives for the probabilistic hot summer years for the current and future climates: (1) pHSY-1 weather file was based on the WCDH, and; (2) pHSY-2 weather file was based on the physiological equivalent temperature (PET). The pHSY-2 weather file uses a PET threshold value of 23°C, which corresponds to a warm thermal sensation or slight heat stress. Both pHSY-1 and pHSY-2 weather files were compared with pDSY files in fourteen UK locations. The study found that both pHSY-1 and pHSY-2 were

more robust than pDSY. The pHSY-1 weather file was suggested to be used to study the severity and occurrences of overheating whereas pHSY- 2 is considered suitable for evaluating thermal discomfort or heat stress.

8.5 DEFINITION OF OVERHEATING

Overheating is a major health concern in buildings due to high indoor temperatures that may exceed the outdoor temperature in some building types such as multi-unit residential buildings (Touchie et al., 2016). Overheating may be present under regular summer climates and are worse under extreme heat events. Furthermore, future climate warmings are expected to worsen the overheating issue. Climate resilient design of buildings should therefore be implemented in retrofitted and new buildings to limit such health threat to vulnerable building occupants.

Overheating is a consequence of the effect of the outdoor climate. However, building construction characteristics (e.g. insulation levels, air leakage rate, proportion of windows, solar shadings, and other relevant factors), and operation of building services (i.e. air-conditioning, and ventilation systems) may influence the degree of overheating in buildings. Furthermore, occupant behavior (e.g. use of appropriate clothing; employ ventilation means such as free standing or ceiling fans, opening windows, etc.) and physiological and psychological adaption to warm climates may exercise a significant influence on the overheating sensation. Indeed, results from field measurements have determined that occupants in buildings without air-conditioning were more tolerant to heat than occupants in air-conditioned buildings (Touchie et al., 2016). In addition, the health impact of daytime overheating may be exacerbated by high nighttime temperatures that may induce sleep disturbances, particularly in urban cities. Studies found that the quality of sleep starts to decrease when the indoor temperature departs from 24°C and some guidelines recommend that bedroom temperatures should not exceed 26°C (CIBSE, 2015). However, maintaining more than one threshold temperature in residential buildings requires the air-conditioning of buildings to be multi-zone controlled, which is not common in most residential buildings that use a single thermostat. A practical overheating metric thus needs to be developed for resilient design of buildings to protect the health of occupants and that provides a minimum penalty from the generation of greenhouse gas emission from excessive energy use.

There is no universal or agreed-upon definition of overheating in buildings (Anderson et al., 2013; ZCB, 2016). The current definitions are mostly based on the threshold temperatures of the static or adaptive thermal comfort for healthy people (CIBSE, 2015; Arcipowska et al., 2015; Mohamed and Hansen, 2017). Vulnerable people who would suffer the most from excessive heat are therefore not explicitly addressed. Heat-stress or health-based threshold temperatures for overheating are very scarce due to limited data on the building indoor thermal conditions (ZCH, 2016). Furthermore, the current heat alert and response systems of communities, which are based on the regional or local definition of extreme heat events, are not linked to overheating in

buildings to avoid any health impact on vulnerable building occupants. Overheating criteria that are used worldwide are summarized below.

8.5.1 CIBSE overheating criteria

CIBSE was the pioneer in developing a best practice guide for overheating in dwellings, offices and schools (CIBSE, 2005). In its first version, the CIBSE's overheating criteria were based on a single temperature threshold exceedance as follows (CIBSE, 2005; 2006):

For residential buildings

- Bedroom temperature should not exceed 26°C for 1% of the annual occupied hours;
- Living room temperature should not exceed 28°C for 1% of the annual occupied hours

For schools and office buildings

- Space temperature should not exceed 28°C for 1% of the annual occupied hours

Those criteria were found to be inadequate as they do not take into account the adaptation of building occupants to warm climates, particularly in free running (not air-conditioned) and naturally ventilated buildings. In those buildings, occupants are acclimatized to warmer conditions, and are given more opportunities to restore thermal comfort when they experience thermal discomfort. The CIBSE's criteria were therefore revised to include the adaptive thermal comfort given in the European EN15251-2007 Standard. CIBSE recommends that for new or retrofitted buildings under a free-running mode, the threshold temperature should conform to Category II (new build) in the BSEN15251-2007 Standard. For such buildings the maximum acceptable temperature (T_{max}) can be calculated from the running mean of the outdoor temperature (T_{rm}) using the formula:

$$T_{max}(^{\circ}C) = 0.33 \cdot T_{rm} + 21.8 \quad (3)$$

CIBSE (2013) established three criteria for overheating based on the deviation of the operative temperature from the maximum comfort temperature of equation (3)

Criterion 1: The number of hours during which the operative temperature is greater than the maximum comfort temperature by at least one degree (K) during the non-heating period from May to September inclusive should not be more than 3% of the occupied hours.

Criterion 2: This sets the severity of overheating (i.e. temperature rise and its duration.) in terms of the Daily Weighted Exceedance (DWE) that should not exceed 6 in any one day. DWE is calculated as the summation over a day of the exceedance number of hours (H_i) weighted by the bins ($i = 0, 1, 2, 3K$, etc.) of the operative temperature (T_{op}) rise above the maximum comfort temperature, and is given as:

$$DWE = \sum H_i (T_{op} - T_{max})_i = H_0 \cdot 0 + H_1 \cdot 1 + H_2 \cdot 2 + H_3 \cdot 3 + \dots \leq 6 \quad (4)$$

Criterion 3: The absolute maximum value of the indoor operative temperature shall not exceed the comfort maximum temperature by 4K. This criterion sets the limit of the indoor operative temperature where the available adaptive opportunities to building occupants cannot restore thermal comfort during extreme heat events.

For Category II buildings with mechanical ventilation or cooling, the overheating criterion uses Fanger's PMV scale limit of 0.5 (equivalent to 26°C for typical summer conditions).

8.5.2 DfES overheating criteria

The Department for Education and Skills (DfES) in the UK has issued various versions to control overheating in classrooms of school buildings in the UK. The first version, as described in the Building Bulletin BB87 (DfES, 2003), used the CIBSE (2006) criterion to limit overheating in classrooms to 28°C for less than 80 hours of the annual occupied hours during the summer period from May to September excluding August. The overheating criterion was relaxed in 2006 according to BB101 (DfES, 2006) to include a combination of the following rules:

- No more than 120 hours when the classroom temperature exceeds 28°C during the normal occupied hours (9:00 AM to 3:30 PM), Monday to Friday, from May to September excluding August.
- The classroom temperature should not exceed the outdoor temperature by more than 5°C on average.
- The classroom temperature should not exceed 32°C when the space is occupied.

Despite these rules that help avoid overheating in schools, some schools were nonetheless found to suffer from being too hot in summer and thus offering poor thermal comfort of (Montazami and Nicol, 2013). The DfES has therefore issued new guidelines for overheating based on the adaptive thermal comfort criteria given in the EN15251-2007 standard (CEN, 2007). These guidelines are similar to the three criteria of CIBSE (2015), but with minor changes as follows (Montazami and Nicol, 2013):

Criterion 1: The number of hours during which the operative temperature is greater than the maximum comfort temperature of Category I or II buildings by at least one degree (K) during the non-heating period from May to September inclusive should not exceed 40 hours or 3% of the annual occupied hours, whichever is smaller.

Criterion 2: The DWE should not exceed 10 in any one day, and where the DWE is calculated as follows:

$$DWE = \sum H_i (T_{op} - T_{max})_i^2 \leq 10 \quad (5)$$

Criterion 3: The absolute maximum value of the indoor operative temperature shall not exceed the comfort maximum temperature by 4K during the occupied hours.

8.5.3 ZCH criteria

The Zero Carbon Hub (ZCH, 2016) has provided some recommendations to assess the overheating risk in dwellings in the UK. The end goal of the recommendations was the development of a mandatory national minimum standard for the construction sector to address the risk of overheating in new build homes during

warmer summers. The ZCH represents nearly 100 different organisations, and its recommendations were drawn from evidence-based and expert views and advice of housebuilders, housing associations, local authorities, professional bodies and technical experts. The recommendations use expert views to screen-out the likelihood of the overheating risk followed by building simulation for a detailed evaluation under the current or future climate. The ZCH overheating criteria are similar to those given in the CIBSE Guide A (2006), and summarized below:

- Bedroom nighttime temperatures should not exceed 26°C for more than a specified percentage (not defined yet) of occupied hours.
- For naturally ventilated buildings, the threshold temperatures for adaptive thermal comfort should be used. Threshold exceedance is allowed for a specified percentage of the occupied hours.
- For mechanically ventilated buildings or naturally ventilated buildings but with limited opportunities for window openings, a fixed temperature threshold (28°C) should be used. Threshold exceedance is allowed for a specified percentage of the occupied hours.

8.5.4 Passive House Institute criteria

The Passive House Institute defines overheating when the indoor temperature exceeds 25°C for more than 10% of the annual occupied hours (Feist et al., 2012).

8.5.5 USGBC criteria

The U.S. Green Building Council (USGC) has recently adopted an overheating criterion for thermal resilience under the new building credit given for Passive Survivability and Functionality During Emergencies (Overbey, 2016). The overheating criterion uses the Standard Effective Temperature (SET) and requires simulation to demonstrate that a building's interior environment will maintain “livable temperatures” during a power outage that lasts seven days during the peak summertime of a typical year. For residential buildings, the SET should not exceed 86°F (30°C) for more than 9 SET °F degree-days (or 216 °F SET hours) during a one week period. For non-residential buildings, the SET should not exceed 86°F (30°C) for more than 18 SET °F degree-days (or 432 °F SET hours) during a one week period.

9. CONCLUSIONS

It is unequivocal that the climate has been warming over the past decades and is projected to worsen in the future. Overheating of building interior spaces as may arise from global warming and extreme heat events has been identified as a major concern to the comfort and health of vulnerable occupants, overloading of building HVAC systems, and straining of utility demands. In this report a review of literature has provided a state-of-the-art of the effects of climate change on overheating of building interior spaces and its consequences on the heat-related health of building occupants. Close to 200 technical articles and guides have been reviewed. The review included the following:

Effect of heat on human health

This included studies on the physiological response of people to heat and its potential effect on human health. The effect of heat on human health is a well-known topic in the medical discipline as it directly leads to illnesses and tissue injury or damage. Heat-related illnesses and injuries develop when the body core temperature is higher than 37°C, resulting in heat cramps, heat exhaustion or fatal heat stroke. Vulnerable people such as the elderly, people in sickness, and children are the most affected by heat due to limitations of their thermo-regulatory systems.

Climate change effects

This included a review of various modeling approaches to predict future climate change and extreme heat events and the need for generating the required hourly weather data for building thermal simulation. Climate change is due to natural factors and anthropogenic (human-made) climate forcings. The World Meteorological Organisation considers 30 years as the minimum period to smooth out the natural variability of the climate. Human-made forcings accumulate over decades and their effect on climate is discernible over longer decadal periods of time. Extreme climate events may occur within the 30 year period, but over the long-term the effects of climate change influence their occurrence frequency, duration, and intensity. The Inter-governmental Panel on Climate Change (IPCC) produced future climate data for the entire globe using an ensemble of coupled global circulation climate models with low spatial resolution (~110 to 550 km) and four representative concentration pathways: RCP2.6 scenario with current emission data, depicting aggressive future climate mitigation; two intermediate scenarios RCP4.5 and RCP6; and RCP8.5 with a high emission scenario. Temperature can be predicted with a high confidence as it is greatly affected by the anthropogenic forcings. Extreme climatic events (e.g. heat waves, wind storms, precipitation) are, however, difficult to predict as they relate to both natural factors and anthropogenic forcings. Extreme heat events are an exception and can be predicted with a high confidence as they are closely related to temperature. Regional climate downscaling techniques are used to produce regional climatic data of high spatial resolution (< 50 km) to undertake hourly computer simulation. Climate observational records have shown that the average temperatures across Canada have increased on average by 1.3 °C over the past 50 years, approximately twice the global average. The degree of warming has been found to vary spatially, temporally, and for different climate indices. Stronger increases have been recorded for the daily minimum temperatures than for the 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. The long-term temperature forecasts made from the results derived from the IPCC models suggest a mean warming of approximately 2 °C to 6 °C in the average temperatures across Canada for the different emission pathway scenarios. The projected changes vary spatially over Canada with some provinces having higher warming magnitudes than others. The provinces of Nunavut, Northwest Territories, and Manitoba are consistently projected with significantly higher warming than the rest of the Canada. The provinces of Saskatchewan and Yukon Territory also fall marginally above the Canadian average.

Extreme Heat Events (EHE)

The review included various definitions of extreme heat events, studies on historical occurrences of EHE around the world, and health impact studies of EHE on the mortality and morbidity of the population. There is currently no specific definition of EHE which is accepted worldwide. The challenge resides particularly in the selection criteria of the threshold values for the intensity and duration of EHE. The Canadian heat alert system uses a combination of humidex, and the daily maximum and minimum temperatures for a few climatic locations for each province. The EHE-related health outcomes include mortality and morbidity. Mortality is well studied around the world. However, mortality studies have many confounding factors (e.g. air pollution, population socioeconomic status, etc.), and the outdoor temperature is typically used as the predictor for excess mortality due to EHE, which is different than the indoor temperature to which most people (up to 90%) are exposed when present in residences, schools, or workplaces. Morbidity studies have been very limited due to the lack of publicly available data.

Risk factors for EHE-related health of people

The possible risk factors were summarized for heat related health issues including those for vulnerable people, environmental factors, community factors, and factors relating to the built environment.

Heat related metrics

The various thermal comfort and heat stress indices developed in the past were summarized in this section. The indices included thermal comfort metrics, physiological heat stress metrics, empirical (or bio-meteorological) metrics and epidemiological metrics. There are more than 100 metrics, but a few of these are universally used for buildings (e.g., thermal comfort) and occupational heat and safety guides and standards. All metrics are developed for healthy adult people and there is none that address vulnerable people such as the elderly and children.

Overheating studies

It is evident that summertime extreme heat events from climate change are a potential threat to the comfort and health of people in urban areas. Buildings may play a major role to limit such effects and thereby protect occupants from the harmful outside environment. Buildings influence the indoor thermal conditions under which people (occupants) are exposed most of the time and to which they experience thermal stress. The indoor conditions are a direct consequence of the outdoor conditions, but the severity of indoor conditions depends on many other factors, amongst which are building type (e.g. houses, apartment buildings, schools, hospitals, etc.), internal space usage (i.e. occupancy density, internal heat gains), construction characteristics (i.e. insulation levels, window surface proportions, orientation of facades), and building operation (i.e. air-conditioning use, natural ventilation). Various field measurement and simulation studies have been completed related to the effects of climate change on overheating in different types of buildings and proper adaptation strategies were reviewed. The review also included studies on how various international organisations have responded to limit the risk of overheating through the development of standards and best practice technical

guides. Various definitions of overheating were presented and analysed to develop a suitable definition for the Canadian context.

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