Guide to identifying alert thresholds for heat waves in Canada based on evidence

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September 2016

UQÀM

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UQÀM | Université du Québec à Montréal
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FACE « Faire-face Aux Changements Ensemble » Mieux s'adapter aux changements climatiques au Canada et en Afrique de l'Ouest dans le domaine des ressources en eau
Environment and Climate Change Canada
Environnement et Changement climatique Canada
Health Canada
Santé Canada

Guide to identifying alert thresholds for heat waves in Canada based on evidence

GOALS

The goal of this guide is to identify alert thresholds for heat waves in Canada based on evidence – an important issue in the context of climate change – and to propose an approach for better defining heat waves in the Canadian context in order to reduce the risks to human health and contribute to the well-being of Canadians.

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1 The IRIACC-FACE project (Faire-face Aux Changements Ensemble) is one of a vast array of Canadian projects pertaining to climate change (CC) coming from IRIACC (The International Research Initiative on Adaptation to Climate Change). IRIACC is managed by the IDRC (International Development Research Centre), co-financed by the IDRC, the Canadian Institutes of Health Research, the SSHRC (Social Sciences and Humanities Research Council of Canada) and the NSERC (Natural Sciences and Engineering Research Council of Canada), establishing a unique collaborative network in Canada and abroad. The FACE project's main goal is to support vulnerable populations' adaptation to climate variability and change in Canada, Morocco and Niger. Programmed on a five-year basis (2011 to 2016) and based on three major themes, this project will develop tools to help improve human health, the sustainability and resilience of natural and human systems, and help assist with the transfer, integration and application of CC adaptation knowledge.

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ABBREVIATIONS AND ACRONYMS

BMI ...... Bio-Meteorological Indicator
CCI ...... Commission for Climatology
CDC ...... Centers for Disease Control and Prevention (USA)
CLIVAR ...... CLImate and VARiability
CORDEX ...... Coordinated Regional Climate Downscaling Experiment
CSSS ...... Centre de santé et de services sociaux (Health and Social Services Centre)
ECCC ...... Environment and Climate Change Canada
EPA ...... Environmental Protection Agency (USA)
ESCER ...... Étude et Simulation du Climat à l'Échelle Régionale (Climate study and simulation at the regional scale)
ETCCDI ...... Expert Team on Climate Change Detection and Indices
FAR ...... False alarm rate
GIS ...... Geographic Information System
GDPS ...... Global Deterministic Prediction System
HC ...... Health Canada
HHWS ...... Heat and Health Warning System
HRDPS ...... High Resolution Deterministic Prediction System
INRS ...... Institut national de la recherche scientifique (National institute for scientific research)
INSPQ ...... Institut national de santé publique du Québec (Québec national institute for public health)
InVS ...... French Institute for Public Health Surveillance
IPCC ...... Intergovernmental Panel on Climate Change
IUHI ...... Intra-urban heat island
MDDELCC ...... Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques (Québec Ministry for sustainable development, the environment and the fight against climate change)
MSC ...... Meteorological Service of Canada
MSP ...... Ministère de la Sécurité publique du Québec (Québec Public Safety Ministry)
NCAR/UCAR ...... National Center for Atmospheric Research/ University Corporation for Atmospheric Research
NLDAS ...... North American Land Data Assimilation System
NOAA ...... National Oceanic and Atmospheric Administration
NTSG ...... Numerical Terradynamic Simulation Group
NWP ...... Numerical Weather Prediction
NWS ...... National Weather Service
PD ...... Probability of detection
PHD ...... Public Health Department
RCM ...... Regional Climate Model
RDPS ...... Regional Deterministic Prediction System
RSS ...... Région sociosanitaire du Québec (Québec health region)
SEDI ...... Symmetric Extremal Dependence Index
SOP ...... Standard Operating Procedures
STARDEX ...... Statistical and Regional Dynamical Downscaling of Extremes for European regions
SUPREME ...... SUrveillance and PRevention of the Impacts of Extreme Meteorological Events
Tamb ...... Ambient temperature
Tavr ...... Average daily temperature
Tmax ...... Maximum daily temperature
Tmax90p ...... 90th percentile of Tmax
Tmin ...... Minimum daily temperature
Tskin ...... Skin temperature
UHI ...... Urban heat island
UQAM ...... Université du Québec à Montréal
UTCI ...... Universal Thermal Climate Index
WHO ...... World Health Organization
WMO ...... World Meteorological Organization
WPM ...... Warning Preparedness Meteorologists
WR ...... Weather Region

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Executive summary

Among natural-disaster risks, heat waves are responsible for a large number of deaths, diseases and economic losses around the world. As they will increase in severity, duration and frequency over the decades to come within the context of climate change, these extreme events constitute a genuine danger to human health, and heat-warning systems are strongly recommended by public health authorities to reduce this risk of diseases and of excessive mortality and morbidity. Thus, evidence-based public alerting criteria are needed to reduce impacts on human health before and during persistent hot weather conditions.

There is no universal definition of heat wave or extreme heat, as well as no consensus regarding the terminology used relating to hot weather. Whether from a meteorological (forecast of one to fifteen days), climate (monthly to seasonal forecasts, or even decadal to multi-decadal projections), or health (monitoring of health effects in the short and medium terms) perspectives, the definitions vary according to the area of expertise. Despite the many available studies on the effects of heat waves on human health, including morbidity and mortality, there are also no universal or fixed thresholds or biometeorological indicators used uniformly in warning systems based on weather forecasts. In order to be useful and relevant, these thresholds must adjust not only according to local climatic and weather conditions, but to the degree of the populations' prior vulnerability and exposure and/or human physiological adaptation to heat as well.

The goal of this guide is to identify alert thresholds for heat waves in Canada based on evidence, and to propose an approach for better defining heat waves in the Canadian context in order to reduce the risks to human health and contribute to the well-being of Canadians. This guide is the result of the collaboration among various research and public institutions working on: 1) meteorological and climate aspects, i.e. the Meteorological Service of Canada (MSC, Environment and Climate Change Canada), and the ESCER centre at the Université du Québec à Montréal, and 2) public health, i.e. Health Canada and the Institut National de Santé Publique du Québec.

This guide contains first an overview of the definitions found in the literature, and offers a consensus on the terminology used for heat waves. This is followed by the current public warning system in use at the MSC, along with an inventory of climate and biometeorological indicators used in different countries for applications in monitoring the state of the climate and/or in the health field. A few methods for forecasting the air temperature on various urban and peri-urban scales are presented followed by an overview concerning the various steps in identifying heat wave thresholds and their effects on health. The guide concludes with a discussion on measures and strategies to put in place in order to reduce the adverse impacts of heat waves on human health, and proposes a number of recommendations in the Canadian context. Among them, the authors reaffirm the need for alert thresholds and heat-health criteria development to be adjustable to the local climate and human context, especially considering the strong spatial and temporal variability of weather and climate across Canada. This suggests that the MSC should adjust its heat warning thresholds on those defined by provincial health authorities, according to local conditions, as well as define flexible thresholds depending on the time or period of the year (both in terms of heat intensity and duration). Regarding exposure to extreme hot conditions, there is no doubt that further developments will benefit from improvements in spatial projections taking into account the continued aging of our population, as well as weather forecasts and climate projections available at high-resolution. This should also include modeling research and development at the urban and intra-urban level. Moreover, temperature measurement campaigns should be regularly carried out in large urban centres to further improve local knowledge and surveillance of adverse extreme hot conditions. For this to happen, a concerted collaborative effort among several institutions as well as a diversity of expertise will be required, in particular to update and improve warning systems on a regular basis.

1. Introduction

As they will increase in severity, duration and frequency over the decades to come within the context of climate change, heat waves constitute a genuine danger to human health (IPCC, 2012). The decade from 2003 to 2012 saw the largest occurrence of heat wave episodes since the early twentieth century, particularly from 2009 to 2012 (Mishra *et al.*, 2015).

Among natural-disaster risks, heat waves are responsible for a large number of deaths around the world, as was the case in 1995 in Chicago (Klinenberg, 2002; National Research Council, 2011), in Europe in the summer of 2003 (Hemon and Jougla, 2004; Confalonieri *et al.*, 2007) and in Russia in 2010 (Ryazantzev, 2011). In particular, exposure to extreme heat caused more than 8,000 deaths between 1979 and 2010 in the United States (National Center for Environmental Health, 2013; NOAA, 2015). In the summer of 2010, 11,000 excess deaths were recorded in Russia compared to the previous summer (Rahmstorf and Coumou, 2011; Otto *et al.*, 2012; Revitch and Shaposhnikov, 2012). In France, the 2003 heat wave, the most intense since 1950, resulted in approximately 15,000 deaths between August 1 and 20 (an increase of 60% compared to the average; Laaïdi *et al.*, 2012). With this in mind, the French authorities (for one) have had no choice but to develop a heat and health warning system (Laaïdi *et al.*, 2012).

Excessive heat is dangerous everywhere, as much in the northern countries as it is under tropical climate, as evidenced by the May 2015 heat wave in India where thousands of deaths were reported (*La Presse*, May 31, 2015). The 2015 heat wave in Europe in late June and early July triggered the national heat wave plan in France (*Le Monde*, July 2, 2015). Despite the heat wave plan (including the heat and health warning system), 3,300 excess deaths occurred in the summer of 2015 (from June 29 to August 9) in France, accounting for an increase of 6.5% (*Le Monde*, October 9, 2015).

There is no universal definition of heat wave or extreme heat. Most definitions refer to a period (usually several consecutive days) of exceptionally warm weather conditions that can potentially cause harm to human health (Hayhoe *et al.*, 2004; IPCC, 2014). Several national weather services have therefore developed their own definition at a national or local level. In practice, the term heat wave applies to a very wide range of weather conditions, from moderate to severe, especially in terms of daytime temperatures or other jointly occurring factors such as temperature at night, humidity or episodes of air pollution. Heat waves are a relatively rare phenomenon, in terms of disaster or emergency situations, i.e., when health-risk prevention interventions must be carried out by public services (Kovats and Hajat, 2008). Moreover, despite the many available studies on the effects of heat waves on human health, including human morbidity and mortality (Aström *et al.*, 2013), and perceived morbidity (Bélanger *et al.*, 2015a), there are no universal weather thresholds and/or biometeorological indicators used uniformly in warning systems. In order to be useful and relevant, these thresholds must adjust not only according to local climatic and weather conditions, but also to the degree of the populations' vulnerability and exposure and/or human physiological adaptation to heat as well. Therefore, these alert thresholds cannot be uniform and one must be able to adapt them to the local climate and human context.

However, precise and flexible criteria for determining the health risks associated with heat waves, whether in contingency planning or in alert systems, are not necessarily set or available, and in most cases they do not take into account the ongoing demographic, economic and climate changes. In short, climate and sociodemographic changes will combine to modify or aggravate the vulnerability of populations in the coming decades (Kovats and Hajat, 2008; Watts *et al.*, 2015; Jones *et al.*, 2015). This is particularly the case in Canada, one of the regions of the globe potentially most affected by rising temperatures over the next decades (IPCC, 2013). In Canada as in other industrialized countries, the exposure to heat waves of sensitive populations, e.g. the elderly, is increasing rapidly (Watts *et al.*, 2015). Under conditions of excessive heat beyond a certain threshold, each additional degree Celsius may increase mortality by 2 to 5% (WHO-WMO, 2012). The risk of mortality increases with the duration of the heat wave, as the affected people become more and more vulnerable (WHO-EURO, 2008; Kjellstrom *et al.*, 2008).

In this context, the objective of this guide is to propose an approach to better defining heat waves in the context of the Canadian climate, based on the available evidence. This should ultimately enable health authorities to reduce risks to human health and contribute to the welfare of Canadians during intense heat. This guide is also part of the implementation or improvement of health warning systems related to heat at the national and international level (e.g., WHO-EURO, 2008), on the meteorological scale (forecasting for a few days to a few weeks) as well as on the climatic scale (monthly or seasonal forecasts or projections at the decadal scale).

This document is based on works carried out mainly in Quebec and to a lesser degree in Ontario and Alberta; however, the concepts in this guide can be applicable to other provinces and territories in Canada, e.g. urban centers such as Vancouver or Halifax, and northern communities such as Nunavut, Northwest Territories, etc.

The next Section (2) contains an overview of the definitions found in the literature, and offers a consensus on the terminology used in connection with our guide. Section 3 presents the Meteorological Service of Canada (Environment and Climate Change Canada) current public warning system, followed in Section 4 by an inventory of climate and biometeorological indicators proposed and suggested in different countries for applications in monitoring the state of the climate and/or in the health field. Section 5 identifies a few methods for forecasting the air temperature on various urban and peri-urban scales, while Section 6 develops the various steps in identifying heat wave thresholds and their effects on health. Section 7 concludes this guide with a discussion on measures and strategies to put in place in order to reduce the adverse impacts of heat waves on human health, and it proposes a number of recommendations to that effect in the Canadian context.

2. Overview of terminology and definitions

2.1 HEAT WAVE AND HOT-WEATHER CONCEPTS

Whether from a meteorological (forecast of one to fifteen days), climate (monthly to seasonal forecasts, or even decadal to multi-decadal projections), or health (monitoring of health effects in the short and medium terms) perspective, there is no consensus and the terminology and definitions regarding hot weather vary according to the area of expertise. *Box 1* provides an overview of different definitions and criteria, depending on the field (weather, climate and health), especially with regard to the issuance of heat wave alerts and advisories.

BOX 1. Definitions and criteria for heat waves, according to some weather and health services at the international and national levels.

INTERNATIONAL ORGANIZATIONS: *METEOROLOGY, CLIMATOLOGY AND HEALTH*

WMO (*World Meteorological Organization*) and WHO (*World Health Organization*)

Since 2014, the WMO and the WHO have shared a joint office for climate and health in order to combine knowledge and help coordinate the development and utilization of weather services with the objective of improving public health. Although the WHO recognizes the lack of uniformity in defining heat waves (WMO-No. 1142, 2015), the WMO has proposed a few definitions, some generic, and some referring to specific criteria:

The WMO defines a heat wave as follows:

> *The WMO offers a generic definition of a heat wave: "Marked warming of the air, or the invasion of very hot air, over a large area; it usually lasts from a few days to a few weeks." (International Meteorological Vocabulary WMO-No. 182);*
>
> *Other definitions have also been proposed under the aegis of the WMO, particularly in the context of the Commission for Climatology and Climate Variability (CCL/CLImate and VARiability (CLIVAR); Folland et al., 1999), with regard to the maximum temperature; e.g., when the daily maximum temperature of more than five consecutive days exceeds the average maximum temperature by 5 °C, the normal period being 1961–1990 (Heat Wave Duration Index, Frich et al., 2002);*
>
> *In the WMO's most recent guide, a heat wave is defined as a consecutive period of more than six days when the daily maximum temperature is above the 90th percentile of reference (1961–1990 normals, Warm Spell Duration Index; Klein Tank et al., 2009).*

IPCC (Intergovernmental Panel on Climate Change)

For the IPCC (IPCC, 2013), the definition of a heat wave is based on two parameters: heat (intensity, without reference to humidity) and duration (unspecified number of days), namely:

> *Heat wave – also referred to as extreme heat event – is a period of abnormally hot weather.*
>
> *Heat waves and warm spells have several definitions, and the definitions sometimes overlap. The term "heat wave" can mean different things, depending on how the index in question is formulated and on the resulting application (Perkins and Alexander, 2012).*

BOX 1. Definitions and criteria for heat waves, according to some weather and health services at the international and national levels. *(continued)*

COUNTRIES: *WEATHER AND HEALTH SERVICES*

France

Météo-France (French national weather services) issues heat wave warnings when they predict at least three consecutive days of minimum daily temperatures above 20 °C and maximum daily temperatures above 33 °C (Laaïdi *et al.*, 2012). According to the InVS (French Institute for Public Health), however, it is preferable, as being most relevant to identifying a heat wave affecting health, to use the Bio-Meteorological Indicators (BMI; see Section 4), which are the sliding averages for three consecutive days[2] of daily minimum temperatures (min. BMI) and of daily maximum temperatures (max. BMI).

The thresholds for characterizing excessive heat also vary from one place to another, generally ranging between 5 and 10 °C above the maximum average temperature for that location. Météo-France and the French health authorities use the terms canicule and vague de chaleur, depending on the level of vigilance required and the actions required by the authorities[3].

The Heat Health Warning System (HHWS[4]) has been designed by the InVS in collaboration with Météo-France to facilitate the implementation of prevention and warning measures against weather-related health risks (Laaïdi *et al.* 2012). This system, based on exceeding certain thresholds from the analysis of the link between average temperatures and mortality, offers high-performance indicators in the identification of days associated with significant mortality.

A comparative study on the same data sets for four cities (Chicago, Montréal, Madrid and London), with four types of warning systems (synoptic[5] classification in the United States, average temperatures in France, perceived temperature in Germany, and humidex[6] in Canada), showed that there was little consistency between days considered at risk by the different systems. However, systems based on the average temperatures, such as the HHWS, identify, in general, days associated with the highest excesses in mortality (Hajat *et al.*, 2010).

United States

The ***National Weather Service*** (NWS) defines a heat wave as a period of two or more days of abnormally hot, humid and uncomfortable weather. This definition is based on daily maximum temperature data from the National Oceanic and Atmospheric Administration (NOAA), which keeps records of weather stations across the country (NOAA, 2015).

According to the ***Environmental Protection Agency*** (EPA), a heat wave is a prolonged period of weather hotter and more humid than normal for a given place at that time of year (EPA, 2006).

For the ***American Red Cross*** (Red Cross, 2015), a heat wave is a prolonged period of excessive heat, generally 5 degrees (Celsius) or more above average, often combined with excessive humidity. When a heat wave is expected, the following terms are used, according to the circumstances:

1- Excessive Heat Watch: Conditions are favourable for an excessive heat event to meet or exceed local Excessive Heat Warning criteria in the next 24 to 72 hours.

2- Excessive Heat Warning: Heat Index values are forecasting to meet or exceed locally defined warning criteria for at least 2 days (daytime highs = 40–43 °C).

3- Heat Advisory: Heat Index values are forecasting to meet locally defined advisory criteria for 1 to 2 days (daytime highs = 37-40 °C).

Australia

A heatwave is a period of unusual and uncomfortable hot weather that could negatively affect human health and community infrastructure (such as the power supply and public transport) and services. Concerning the warning system, a temperature threshold has been set for each of the nine districts (Victoria State Government, 2011).

England

The Heat Health Watch Service comprises four levels of response based upon threshold maximum daytime and minimum nighttime temperatures. These thresholds vary by region, but an average threshold temperature is 30 °C by day and 15 °C overnight, for at least two consecutive days (Met Office, 2015).

2 The daily BMI is the average of the D, D+1, and D+2. See http://www.invs.sante.fr/publications/2005/sacs_2005/rapport_sacs_2005.pdf

3 In the context of Vigilance (http://vigilance.meteofrance.com/html/vigilance/guide-Vigilance/dm_chaud.html), in France, *vague de chaleur* is used for the yellow level of heat wave monitoring. When the level increases to orange or red, it becomes a canicule. When it comes to climatology, vague de chaleur is used as this phenomenon is evaluated relative to other values, and temperatures are used (rather than BMIs) in order to allow a comparison across the country.

4 HHWS is part of the national heat wave plan. This is in effect between June 1 and August 31. Should weather conditions call for it, it can be activated earlier and/or maintained beyond August 31.

5 The term synoptic is used in *meteorology* and *oceanography* to describe the phenomena that occur on a large scale. More specifically, a spatial scale of several hundred to several thousand kilometers and duration of several days characterize phenomena of synoptic scales.

6 The humidex index is defined in *Appendix A*.

As suggested in the IPCC report on extreme event and disaster risk management (IPCC, 2012), there is no single definition of a climate extreme, including heat wave, as definitions vary by region and affected area (Stephenson *et al.*, 2008). Most research on extremes is based on the use of indices developed in various projects ((e.g., the European STARDEX project; Goodess, 2003) or the ETCCDI project (Zhang *et al.*, 2011)). These indices can either be based on the probability of occurrence of a variable or a given quantity or on exceeding absolute or relative thresholds (compared to a fixed climatological period), or include more complex definitions associated with duration, intensity and persistence of extreme weather events. Thus, the term "heat wave" can mean very different things, depending on the formulation of the index and the application for which it is required (Perkins and Alexander, 2012). A detailed inventory of climate and biometeorological (heat-related) indicators is provided in Section 4.

Weather thresholds for characterizing heat waves therefore vary from place to place but generally oscillate between 5 and 10 °C above the average maximum temperature for that location (Laaïdi *et al.*, 2012). Other definitions or criteria vary by country and do not necessarily use similar criteria of duration (one to three days or more) or intensity (absolute or relative threshold of daily maximum temperature, Tmax, or even daily minimum temperature, Tmin).

In Canada, the Meteorological Service of Canada (MSC)[7] does not issue heat wave warnings: in fact, this term is not precisely defined by the MSC. Instead, the MSC issues heat warnings when certain criteria (heat and/or humidity) are forecast or observed (see Section 3).

Although the MSC has no formal definition for heat waves, the public and the authorities generally use the terms listed in *Table 1*: the terminology for cold or warm episodes varies according to the time of the year. These terms are most often used to describe abnormally high or low temperatures. A heat wave (extreme heat) is sometimes referred to as "*canicule*" in French. These terms and criteria will be revisited within the framework of a warning-system development. *Table 1* is also a reminder that Canada is a Nordic country. As many studies suggest that cold generally has a higher impact than heat on mortality worldwide (e.g., Gasparrini *et al.*, 2015), a similar work (warning system thresholds based on climate AND health parameters) should eventually be undertaken, regarding cold weather.

7 MSC: Environment and Climate Change Canada (ECCC) federal department responsible for issuing forecasts and weather warnings.

TABLE 1. Terminology currently (informally) in use at the MSC, according to season.

HIGH TEMPERATURES											
MILD					HOT						
Nov.	Dec.	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.
Mild weather					Warm spells						
							Heatwaves (Extreme heat)				

LOW TEMPERATURES											
COLD					COOL						
Nov.	Dec.	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.
Cold wave					Cool weather						
	Extreme cold										

2.2 CRITERIA CONSIDERED IN DEFINING A HEAT WAVE AND CONSENSUS TERMINOLOGY

The absence of semantic consensus, therefore, requires us to establish definitions for the purpose of this guide. The criteria used to define heat waves will hereafter include the known factors, depending on the studies available that characterize these weather hazards and their impacts on human health, within the Canadian context.

In general, the criteria for defining heat waves in most countries or regions of the world involve a period of two to four days of excessive heat (depending on the climate of the sector under consideration), according to temperature threshold values (absolute or relative thresholds). For example, in France, the most effective indicator in all cities analyzed turned out to be the combination of Tmin and Tmax averaged over three days (Laaïdi *et al.*, 2012). Québec adopted a similar indicator with a lower weighting (see Section 6) for the third day of the forecast (Chebana *et al.*, 2013). More recently, Ontario (2015) and Alberta (2016) have adopted a combination of Tmax and Tmin for different areas, over a two-day period. These indicators are based on the historical excess mortality associated with certain thresholds and have been established by the provincial health authorities in collaboration with ECCC.

We will deal in particular with health indicators (mortality, hospitalization, etc.) in Section 6, resulting from direct or indirect effects of heat waves.

In the context of this guide, the term "**heat wave**" will be restricted to the summer season, from June to August (exceptionally in May or September). We will use the term "extreme heat wave" for events that are related to reaching or exceeding thresholds related to excess mortality, given that this term is well rooted in scientific publications and is used by public health authorities. Extreme heat waves occur during the summer when the humidity and/or nighttime temperatures are highest. These definitions are based on criteria that are relevant from a health perspective, and try to align with the most frequent use of the terms in Canada.

In summary, the definitions used in this guide are as follows:

- **Warm spell**: Generic term for any period of at least two days during which temperatures are above the normals (the normals being established over a period of 30 years, according to WMO).
- **Heat wave**: During the summer (June to August), when the maximum daily temperature reaches or exceeds the local normal value by at least 5 °C (calendar day climatology established over 30 years), for at least three consecutive days.
- **Heat**: The MSC uses this term in its weather warnings (see Section 3). Note that the highest temperature ever recorded in Canada (45 °C) was observed in Saskatchewan (in Midale and Yellowgrass), on July 5, 1937 (source: Environment and Climate Change Canada, 2015b) Top Weather Events of the 20th Century).
- **Extreme heat wave**: Term used by some public health authorities in Canada, to designate excessive heat over two to three days or more that can cause a high risk of excess mortality and other potential health impacts.

In Québec, during the five-day heat wave of July 2010 (case presented in Section 4), a daily mortality in excess of approximately 30% was measured (Bustinza *et al.*, 2013). The SUPREME[8] monitoring system was set up jointly by the INSPQ[9], the MSP[10] and the MSC in May 2010. SUPREME is similar to the French HHWS alert plan (see Section 6), with specific thresholds for four Québec regions, identified from the historical risk of heat-related excess mortality (Chebana *et al.*, 2013). SUPREME was developed to guide public health authorities and policy makers (CSSS[11], DSP/PHD[12] and MSSS[13]) during heat waves. It is briefly described in this guide.

8 SUPREME: SUrveillance and PRevention of the impacts of Extreme Meteorological Events (Details provided in *Appendix B*).

9 INSPQ: Institut national de santé publique du Québec (Québec National Institute for Public Health).

10 MSP: Ministère de la Sécurité publique du Québec (Québec Public Safety Ministry).

11 CSSS: Centre de santé et de services sociaux (Health and social services centre – local).

12 DSP: Direction de la santé publique (PHD: Public Health Department – regions).

13 MSSS: Ministère de la Santé et des Services sociaux du Québec (Québec Ministry for Health and Social Services).

Several factors may exacerbate, or reduce, the severity, duration and occurrence of heat waves but also their effects on human health. This includes factors such as:

- Environmental – *related to surface conditions or physiographic features of the site, and air pollution*;

  Heat waves are also often synonymous with air pollution due to associated weather conditions: persistent high-pressure system, sunlight, high temperature, little or no wind, stability of the lower layers of the atmosphere (limiting vertical exchanges and allowing the stagnation of the air near the surface). These conditions result in the formation and/or concentration of pollutants such as ozone, fine particles and a host of chemical compounds.

  During the European 2003 heat wave, weather conditions also contributed to the creation of a photochemical pollution (ozone) episode that was abnormal in its duration and geographical coverage. All these factors contributed to the excess mortality recorded in France during the month of August 2003 (Cassadou *et al.*, 2004), as well as in much of Europe (Kosatsky, 2005). Overall, during a heat wave, the effect of heat as an explanatory factor of mortality is dominant, and the effect of co-occurring smog remains minor, about 5% (Cassadou *et al.*, 2004).

  In Québec, the 2010 heat wave was also accompanied by air pollution, mainly by fine particles and ozone (Denis Bourque [MSC], personal communication, February 2015).

- Human – *related to physiological, behavioural and socio-economic conditions of vulnerable people and their degree of exposure*;

  As mentioned previously, the thermal characterization of a heat wave depends on the local climate and weather, and should therefore reflect the vulnerability of populations exposed to extreme heat events for which they are not acclimatized (see Section 6). The combination of human and spatial relativity prevents the adoption of a universal definition.

- Weather and/or climate – *related to the joint occurrence of Tmax and Tmin or even humidity conditions, depending on time of year*;

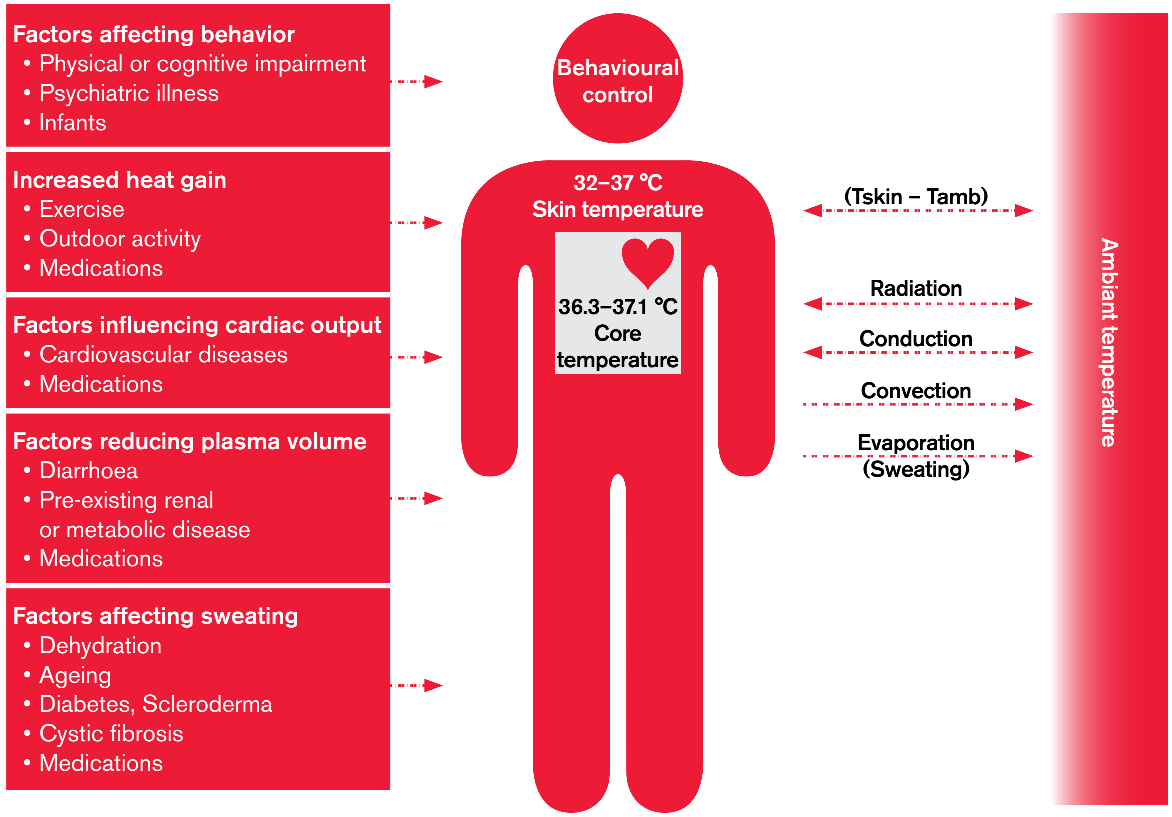
  During heat waves, high daytime temperatures are also often associated with high nighttime temperatures. For example, during the heat wave in the summer of 2003 in France, the Tmax and, significantly, the Tmin, were the highest since 1953 (Cassadou *et al.*, 2004).

  If excessive heat combines with high humidity, the human body temperature-regulation process is compromised. Since the human body cools by the evaporation of sweat, high relative humidity in the ambient air makes this process more difficult, thus limiting skin cooling and therefore thermoregulation of the human body (see *Box 2*).

The humidity is considered an aggravating health factor for populations during heat waves (Chebana *et al.*, 2013) inasmuch as humid heat is more difficult for the body to endure than dry heat (Laaïdi *et al.*, 2012). This is why in North America the relative humidity is often taken into account when issuing heat warnings, even though humidity as such is not part of the definition of a heat wave (see *Box 1* and Section 3). The United States uses the Heat Index when issuing heat warnings, which takes into account humidity (NOAA, 2014). In Section 4, we will elaborate on this concept and present an inventory of climatic and biometeorological indicators most commonly used. We will illustrate the relevance of a particular definition of multivariate criteria in the context of the heat wave of 2010, according to the local and regional weather conditions of southern Québec and Ontario.

BOX 2. Effects of heat on the human body.

Factors affecting human thermoregulation and the risk of heat illness



(Source: WHO, 2008)

Lastly, while heat waves are generally widespread and affect both rural and urban populations, the phenomenon of the urban heat island (UHI) effect is exacerbated during these prolonged periods of extreme heat, especially after several days without precipitation (Martin *et al.*, 2015). We will deal with these phenomena in Section 5, some studies showing that mortality is generally higher in large cities than in rural areas, mostly due to the UHI effect (Dousset *et al.*, 2011). However, there are some heat health impacts in rural areas as well. For example, a study conducted in Ohio found that while more people were affected in urban areas, the mortality rate was about the same between rural and urban areas (Sheridan, 2002).

2.3 ACTION PLANS RELATED TO HEALTH

To be effective, a heat and health-related action plan must be based on the capacity to anticipate heat waves that are likely to have a significant impact, so that public health decision makers have time to set up appropriate preventive measures. The action plan must also include a warning system, based on thresholds of a weather parameter (or a combination of several parameters), to properly assess the risk on health.

Health-related action plans (including warnings systems) during heat waves have been set up in some countries. Among the plans and documents available are:

- **In Europe**: Health action plans for heat (WHO-EURO, 2008), *Improving Public Health Responses to Extreme Weather/Heat-Waves–EuroHEAT: Technical Summary* (WHO, 2009). The EuroHEAT project is co-financed by the WHO and the European Commission, whose aim is to help the public health sector respond better to extreme weather events and heat waves (Matthies *et al*., 2008);

- **In the United States**: *Excessive Heat Events Guidebook* (EPA, 2006; NOAA, 2015; Centers for Disease Control and Prevention (CDC), 2008);

- **In Australia**: *Heatwave Plan for Victoria: Protecting Health and Reducing Harm from Heatwaves (Victoria State Government, 2011)*;

- **In England**: *Heatwave Plan for England: Protecting Health and Reducing Harm from Extreme Heat and Heatwaves* (UK Gov., 2015);

- **In France**: The HHWS relies on a framework agreement between the InVS and Météo-France, developed in 2012 and implemented in the summer of 2013; the HHWS allows to adjust the level of vigilance, originally established in accordance with weather conditions (only), based on health information provided on an ongoing basis by health authorities and the InVS.

In many federations, such as Canada, or the United States, the legal responsibility and the development of these plans fall under the provinces or the states, or other smaller administrative units (such as cities, regions or counties). The plans are often adapted for regional or local characteristics, or for certain clienteles. For example, one can refer to the Québec heat intervention guide (MSSS, 2006) or to others used in other Canadian provinces (Health Canada, 2012). Other guides specifically target health workers (Health Canada, 2011) or workers in general (Adam-Poupart *et al.*, 2012).

3. Alerting the public

3.1 MSC'S CONCEPT OF EARLY (TIMELY) NOTIFICATION

The ultimate goal of any weather alert system comes down to helping in making decisions and taking actions to mitigate the impacts related to risks posed by severe weather conditions.

For about ten years, both formal and informal partnerships have been established between Environment and Climate Change Canada (ECCC) and various regional organizations, such as the INSPQ in Québec. Under these agreements, the MSC provides weather information to partners who may then issue alerts based on their own criteria (extreme heat as defined in Section 2) and disseminated to those concerned (e.g., for health needs; see Bustinza and Lebel, 2012).

Meanwhile, ECCC, in collaboration with several partners, also began developing an approach based on identifying, communicating and reducing risk associated to hydrometeorological hazards. In such an approach, identifying and communicating risk are carried out as early as possible, taking into account both the uncertainty inherent in any forecast and the response capacities of organizations (e.g., public health authorities). Based on best practices developed, among others, in Europe (Laaïdi *et al.*, 2012) and pilot projects in Canada, this approach seems the most promising one for optimizing preparation efforts regarding heat waves and thus ultimately reducing the impacts associated with those events.

Since heat waves can generally be detected several days in advance, the MSC may bring the threat to the attention of its partners more quickly (up to a week in advance). The various partners involved, including MSC, may then build together on the principles of early (timely) warning notification to alert the authorities and vulnerable populations so that they can implement the actions necessary for preparing and/or protecting themselves. Such an approach has the potential to reduce significantly the risks associated with extreme heat events.

Of course, the earlier the notification, the greater the uncertainty that the event will occur at the said times and at the said places. However, by updating the notification on a daily basis, the uncertainty gradually decreases, as the onset date of the phenomenon approaches. The MSC tries to minimize false alarms while maintaining a useful lead-time of the warning for partners and the public. There is a fine balance between the probability that an event will occur well in advance (in order to plan risk-reducing actions) and the possibility of a false alarm, which would reduce the credibility of the messenger and the impact of the message (cry wolf effect). However, recent research (Joslyn and LeClerc, 2013) has shown that people can make (good) decisions under uncertainty, when it is expressed in an appropriate fashion: a probabilistic estimate of the uncertainty improves the quality of the decision-making, by providing more credible forecasts, despite occasional false alarms.

3.2 RECOGNIZING WEATHER PATTERNS

Although the MSC does not issue heat wave warnings, meteorologists will often contact health authorities as soon as they detect a “weather pattern” (synoptic signal) conducive to this type of events. The weather pattern associated with heat waves has a signature that is relatively easy to recognize by experienced meteorologists on numerical models used in predicting the weather. Although the signature can be identified almost a week in advance, the fact remains that it is a forecast, and the precise beginning (or end) of such an episode – or the temperature – cannot be predicted with as much certainty as one or two days before the onset of the event (see *Table 3*).

3.3 MSC CRITERIA FOR ISSUING HEAT WARNINGS

With respect to heat, the MSC has identified a number of temperature thresholds that, when forecast or reached, trigger the issuance of warning messages. These messages refer to forecast temperatures and/or humidex; they are usually issued without regard to the duration of the phenomenon (even only for one hour). More recently, in Ontario (2015), and now in Alberta (2016), new criteria defined and implemented in collaboration with health authorities include duration (at least two days).

The thresholds determined by the MSC are based on climatology, that is to say, taking into account the relative rarity of the phenomenon, without an *a priori* relationship to the potentially harmful effects on health. These thresholds were established decades ago, long before a dialogue was initiated with partners such as Health Canada. In addition, back then, little attention was given to the UHI effect, which has been the subject of numerous studies and much concern over the past two decades (see Section 5), since temperature was measured mainly at airports and in rural areas, which were not much affected by the UHI effect.

Table 2 specifies MSC's official *Standard Operating Procedures* (SOPs) for issuing heat warnings (Public Alerting Criteria, e.g., Environment and Climate Change Canada, 2014). These guidelines define the regional threshold warnings and help MSC forecasters' decision-making in issuing and terminating the warnings, through the various parts of Canada. Except in British Columbia, where the areas covered by the warning program are clearly identified, *Table 2* may give the impression that the heat-warning program covers all sectors in other provinces. In fact, the temperature and humidity conditions required for issuing a heat warning are never observed, nor forecast, in the North (Nunavik, Nunavut, Northwest Territories, Yukon, and northernmost parts of most provinces). This does not mean that conditions below current warning thresholds do not represent a threat to northern populations, which are much less acclimatized to heat. Eventually, criteria specific to these areas should be determined in collaboration with health authorities, especially given the context of rapid and significant warming in subarctic regions in recent decades (Cohen *et al.*, 2014) and in the future (see Chapter 11 in IPCC, 2013), as well as the vulnerability of the local population.

Table 2 is also based on the assumption that a province's climate is homogeneous, which is not the case (see Section 4). For example, in Québec, the MSC threshold for issuing a heat warning is the same for Sept-Îles as it is for Montréal, which nevertheless have very different climates, and with populations that are acclimatized or adapted to different conditions (particularly in terms of summer temperatures; see *Appendix C, Figure C.1*). In addition, the temperature thresholds presented in *Table 2* do not take into account the UHI effect in cities where populations do not enjoy the night cooling that can help people in rural areas cope with extreme heat events.

TABLE 2. MSC Standard Operating Procedures for issuing heat warnings in Canada.

REGION(S)	TEMPERATURE AND HUMIDEX (THRESHOLDS)
British Columbia Regions Covered: Greater Vancouver, Fraser River Valley, Howe Bay, Whistler and the Sunshine Coast	Warnings issued when: 1. The average daily temperature at 14:00 (local time) and the forecast for the next day at Vancouver Airport are expected to be ≥ 29 °C; **or** 2. The average daily temperature at 14:00 (local time) and the forecast for the next day at Abbotsford Airport are expected to be ≥ 34 °C.
Alberta	Warnings issued when these thresholds will be met for <u>two days</u> or more: 1. South Zone: Tmax > 32 °C and Tmin > 15 °C; 2. Calgary, Central, Edmonton and North: Tmax > 29 °C and Tmin > 14 °C.
Manitoba, Saskatchewan, NT and Nunavut	Warnings issued when the temperature is expected to be ≥ 40 °C, the humidex ≥ 40, and the dew point to be ≥15 °C.
Ontario	Warnings issued when these thresholds will be met for <u>two days</u> or more: 1. Windsor–Essex–Chatham–Kent: Tmax ≥ 31 °C and Tmin ≥ 21 °C or humidex ≥ 42; 2. Southern Ontario excluding Windsor–Essex–Chatham–Kent: Tmax ≥ 31 °C and Tmin ≥ 20 °C or humidex ≥ 40; 3. Northern Ontario: Tmax ≥ 29 °C and Tmin ≥ 18 °C or humidex ≥ 36.
Québec, except in Nunavik	Warnings issued when the humidex is ≥ 40 and when the temperature is ≥ 30 °C and these two conditions persist for at least one hour, or when the temperature is ≥ 40 °C. *Authors' note: the highest temperature ever recorded in Québec was 40 °C, in Ville-Marie (Témiscamingue), on July 6, 1921.*
Nova Scotia, New Brunswick, Prince Edward Island, and Newfoundland and Labrador	Warnings issued when the temperature is expected to be ≥ 40 °C, or the humidex ≥ 40, for at least one hour.

(Source: Environment and Climate Change Canada 2014, and 2015a)

Note: The new criteria for Ontario were established in collaboration with public health authorities and have recently been (2015 and 2016) implemented. The criteria have been revised in Alberta, in collaboration with public health authorities and the new thresholds are being implemented in 2016.

3.4 FORECASTING HEAT WAVES AT THE MSC

As stated previously, within the MSC, none of the organization's programs deals specifically with heat waves, and there is no standard definition. The programs revolve more around temperatures and humidex (as suggested in *Table 2*), and except for Ontario and Alberta, without duration as a consideration.

However, the MSC can make the public aware of excessively hot and/or humid conditions that will persist for several days via a special weather report. Warning Preparedness Meteorologists (WPM) can also directly notify public health partners of impending potentially threatening conditions. Furthermore, some provinces (Québec, Ontario, Manitoba and Alberta) have agreements between ECCC and public health partners that help them inform the public about forecast or observed heat and/or humidity conditions.

Temperature and humidity forecasting is based largely on the use of numerical weather prediction (NWP) models. Numerical weather models can be deterministic (from 1 hour to 10 days) or probabilistic (from 12 hours to 16 days). Deterministic models offer only one possible "scenario" while probabilistic models (also called ensemble forecasts[14]) offer many plausible scenarios, with associated probabilities. We will describe the deterministic models in use at ECCC in Section 5.

The meteorologists' expertise is also put to use, particularly at finer spatial scales (e.g., local) and shorter time scales (e.g., hours). One can summarize the forecasting process as follows:

- **Five to seven days before the onset of a heat episode** (usually accompanied by humidity): Numerical forecasts, especially probabilistic forecasts, can detect not only the "synoptic signature" of the phenomenon but also assess the uncertainty of the forecast. Meteorologists can also identify areas that are most likely to be affected.

- **Two to five days before the onset of the heat episode**: Numerical models allow the forecasters to assess the persistence of the phenomenon's synoptic signature. Probabilistic forecasts remain relevant in defining the onset, duration and geographical extent of the event.

- **One to two days before the onset of the heat episode**: Shorter-term (usually deterministic) models help to determine as precisely as possible the beginning of the phenomenon, its intensity or severity, its likely duration and its geographical extent.

- **During the heat episode**: The focus is primarily on the finest spatio-temporal scales available to define as precisely as possible the warmest sectors, especially in urban areas. Forecasts are fine-tuned using high-resolution models and geostatistical methods (see Section 5), real-time analysis and meteorologists' knowledge of local effects.

In addition to temperature and humidex, the MSC also takes into account precipitation as it affects the length of a heat episode, or even its intensity. Sometimes rain showers contribute to reach the criteria for heat warnings by increasing the humidity, or, conversely, they may bring about a temporary or permanent end to a heat episode by cooling the atmosphere. Large amounts of rain are not necessary for such effects to be observed.

3.5 VERIFYING WARNINGS AND FORECASTS

Since the heat-warning verification criteria are linked only to the temperature and humidex forecast or observed, regardless of the duration of the event (except in Ontario and Alberta), the MSC does not verify heat waves strictly speaking. That said, heat warnings are subject to verification based on the thresholds outlined in *Table 2*. We should also mention that SOPs require advance notice of at least 12 hours (18 hours in Ontario) before the start of the event (i.e. before reaching the warning threshold) for this warning to be a "success", i.e. an "accurate" forecast. Some major events (such as the heat wave of July 2010 in Montréal, presented in Section 4) have been the subject of assessment reports (*a posteriori*), but this practice is not systematic.

The MSC performs an automated Tmax and Tmin check for 23 major cities across the country. *Table 3* provides an example of verification during the first seven forecast days for the year 2015 (the most recent available data) with respect to daily (a) Tmax and (b) Tmin forecast for 23 Canadian cities. The spread of ± 3 °C used for the verification was chosen by the MSC after two national surveys conducted in 2007 and 2011 (Ekos Research Associates Inc., 2007 and 2011) and this may not necessarily be suitable for certain issues (e.g., temperatures above 30 °C or around 0 °C). In other words, these results provide just an overview of the current temperature forecast capacity as a function of the forecasting lead-time: for example, in 2015, from July to September, the Tmax was accurate 96% of the time (average of the 23 cities considered) when forecast 1 day ahead, 93% of the time when forecast 2 days ahead, etc. It is also assumed that those results are representative for the whole country, not only the cities under consideration.

14 Ensemble forecasting is a weather-prediction technique in which one or more numerical prediction models are used several times (for the same forecasting period), based on initial conditions differing from each other by small values or small differences (initial perturbations) that are compatible with existing uncertainties regarding the knowledge of the initial state of the atmosphere (see Palmer *et al.*, 2002).

TABLE 3. a) Tmax verification and b) Tmin verification for 23 Canadian cities in 2015.

FORECASTING LEAD-TIME FOR A) TMAX	PERCENTAGE (%) OF ACCURATE PREDICTIONS (± 3 °C) FOR 2015			
	JANUARY–MARCH	APRIL–JUNE	JULY–SEPTEMBER	OCTOBER–DECEMBER
1 day	94	94	96	94
2 days	90	88	93	91
3 days	81	81	89	85
4 days	78	75	84	82
5 days	70	71	80	76
6 days	63	68	77	68
7 days	56	65	71	63

FORECASTING LEAD-TIME FOR B) TMIN	PERCENTAGE (%) OF ACCURATE PREDICTIONS (± 3 °C) FOR 2015			
	JANUARY–MARCH	APRIL–JUNE	JULY–SEPTEMBER	OCTOBER–DECEMBER
2 days	87	93	96	91
3 days	83	90	95	87
4 days	72	88	92	80
5 days	63	82	87	77
6 days	59	81	85	71
7 days	55	77	81	66

Note: The forecast is issued one to seven days before the values are observed at the stations of the 23 cities (two to seven days for minimum temperatures, since verification begins with the forecast issued at 05:00 [local time], after the first night is already completed).

As shown in *Table 3*, we see a logical decrease in the percentage of correct predictions as the forecasting lead-time increases. The most accurate predictions occur during the summer and are slightly less reliable during the other seasons (especially for five to seven days). In addition, from one city to another, the results (not shown here) sometimes vary considerably. In general, cities for which climate has less variability from day to day or on an intra-monthly scale (e.g., in the Maritime Provinces) obtain better forecasts results than cities where climate has large intra-monthly fluctuations (e.g., in the Prairies Provinces or Central Ontario and Central Québec; see *Appendix C*, *Figure C.2*).

A quick review of verification data for previous years (not shown) shows a gradual improvement with time in capacity for forecasting temperatures. The Canadian results are consistent with those of Météo-France: the quality of forecasts is improving by one day every ten years: today, four-day forecasts are as reliable as three-day forecasts of the early 2000s (http://www.meteofrance.fr/prevoir-le-temps/la-prevision-du-temps/les-performances-des-previsions). Forecasting results from the NWS (United States) are also more reliable than before; a study found that forecasting accuracy for the seventh day is now equal to what it was for the third day thirty years ago (Novak *et al.*, 2014).

The improved forecasting is the result of scientific and technological advancements: increased model resolution, availability of satellite data since the early 1980s (Eyre, 2007), better assimilation of available data by the models, improved model formulation, and increased computational power of supercomputers used in forecasting.

While most weather centres also verify their forecasts, the methodologies and thresholds used vary from one country to another, according to their own needs and capabilities. For example, in the United Kingdom, weather services (Met Office) verify temperatures according to a spread of + 2 °C between the expected and the observed value (http://www.metoffice.gov.uk/about-us/who/accuracy/forecasts). The NWS, on the other hand, uses the amplitude of the mean absolute error (Fajman, 2011). Météo-France verifies its forecasting somewhat along the same lines as the NWS. According to Météo-France, the 24-hour temperature forecast at a point of interest has an average accuracy of about 1 °C; seven days ahead, the precision is about 3 °C. (http://www.meteofrance.fr/prevoir-le-temps/la-prevision-du-temps/les-performances-des-previsions). The study by Novak *et al.* (2014) gives orders of magnitude comparable for the NWS. In light of these data, it would be noteworthy to know the accuracy of MSC forecasts in terms of difference (or error) between prediction and observation.

At the MSC, the verification exercise related more specifically to heat warnings consists of evaluating whether or not the observed weather conditions correspond to the criteria described in *Table 2*. Unlike the daily verification of forecast quality, which is automated, verification of heat warnings requires that a meteorologist analyze the event, after the fact. This verification also covers situations in which heat conditions are observed but have not necessarily been forecast (missed cases). Warnings verification is also performed on a spatial scale, not at a single point as for the automated verification shown in *Table 3*. This can also imply using formal (e.g., federal and provincial entities such as ECCC, MDDELCC[15], etc.) or informal (e.g. volunteer observers, Wunderground, etc.) observation networks.

15 MDDELCC: Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques (Québec Ministry for sustainable development, the environment and the fight against climate change).

The MSC also performs an automated verification of precipitation forecasts. The verification procedure for precipitation is different from the one for temperature, since the precipitation forecast is usually expressed in the form of a percentage (probability). For information, a 40% probability of precipitation for a given territory means that, for the period covered by the forecast, any point in that territory has four in ten chances of receiving at least 0.2 mm of rainfall (measurable value). The verification results for precipitation, as for most forecasts involving probabilities, are expressed as Brier Scores[16]. *Table 4* shows the results (positively oriented Brier Score) of the verification of forecast precipitation for 2015 (for the same 23 Canadian cities as shown in *Table 3*).

16 The *Brier Score* (Brier, 1950) is probably the most commonly used verification measure for assessing the accuracy of probability forecasts (Murphy, 1973). The score is the mean squared error of the forecasts vs the observations. The Brier Score ranges from 0 for a perfect forecast to 1 for the worst possible forecast (for further information see: http://www.cawcr.gov.au/projects/verification/ and http://www.wmo.int/pages/prog/arep/wwrp/fvr.html). However, the MSC uses a positively oriented Brier Score, (more intuitive), where 1 would be a perfect forecast, and 0 the worst forecast. For further information, an overview of forecast verification is given in Casati *et al.* (2008).

TABLE 4. Precipitation verification for 23 Canadian cities in 2015.

FORECASTING LEAD-TIME	BRIER SCORE (PRECIPITATION FORECASTS) FOR 2015			
	JANUARY–MARCH	APRIL–JUNE	JULY–SEPTEMBER	OCTOBER–DECEMBER
1 day	.86	.90	.90	.86
2 days	.84	.88	.88	.83
3 days	.80	.86	.86	.80
4 days	.78	.85	.86	.79
5 days	.77	.84	.85	.77
6 days	.76	.83	.85	.77
7 days	.75	.83	.84	.76

Note: The forecast is issued one to seven days before the observed values at the stations of the 23 cities.

The trends observed in the precipitation verification results are the same as for temperature; i.e., a logical decrease in forecasts accuracy as the forecast lead-time increases, and better results in summer than in other seasons. A review of several years' results (not shown here) once again indicates a gradual improvement in the quality of forecasts with time, due to the technological and scientific improvements outlined above.

Regarding rainfall warnings, a meteorologist will verify only amounts of precipitation (forecast or observed) exceeding pre-determined thresholds. This section does not cover procedures for rainfall warnings, since, as mentioned before, one does not need large quantities of rains to trigger or end a heat episode.

For the time being, the MSC does not issue heat wave warnings and consequently has not developed a verification system for such events. In any case, as suggested by other meteorological services worldwide and health agencies that use weather information for effective warning programs in order to protect public health, developing specific criteria that help in assessing "excessive heat due to weather conditions" (see CDC, 2012) is essential, and so will be the verification process for this type of warnings.

4. Inventory of climate and biometeorological indicators

The inventory of climate and biometeorological indicators presented here is the result of expert review and judgment. This is based on various experiences and valuable guidances from different background, and these indicators are in regular use in weather forecasts (e.g. from WMO guidelines and/or national weather services), climate change and impact (health) studies (e.g. from IPCC and CLIVAR teams), and health agencies (e.g. from INSPQ, Heath Canada, InVS, etc.) in Canada and abroad.

4.1 DEVELOPING HEAT-RELATED INDICATORS: BACKGROUND

The heat factor of the ambient air is a major health problem and has been linked in many studies to significant excess mortality (e.g., Chebana *et al.*, 2013), as was the case during heat waves in Europe, the United States and Australia (e.g., Semenza *et al.* 1996; Fouillet *et al.*, 2006; Tong *et al.*, 2010, respectively). Many studies have used a variety of measures or heat-related indicators; for example, through the use of Tmax and Tmin, apparent temperature and/or through the use of other biometeorological and human comfort (or discomfort) indices to assess population vulnerability to heat stress (e.g., Hoeppe, 1999; Spagnolo and de Dear, 2003; Nicholls *et al.*, 2008; Barnett *et al.*, 2010; Vaneckova *et al.*, 2011; Oleson *et al.*, 2015).

Among the proposed definitions, we will distinguish between: a) The climatic indices used when evaluating heat waves (historic and future climate), either from observed or simulated data, without regard necessarily to using them for specific applications in the health field (e.g. mainly based on generic definition proposed by climatologists and used in climatic studies; see IPCC, 2012 and 2013), and b) Combining biometeorological indices consisting usually of several (meteorological and health) variables defined specifically for applications on human morbidity and mortality.

4.1.a. Heat wave climate indices

The diversity of heat wave climate indices in the scientific community demonstrates the lack of terminology consensus (Smith *et al.*, 2013), while most "generic" definitions have been proposed for general applications on a global or continental scale. Among the definitions commonly proposed for heat waves, most often we find the use of criteria that include an individual (or isolated) occurrence of daily temperature values (most frequently Tmax) exceeding absolute or relative thresholds, and for various durations. In particular, these definitions combine:

- Absolute Tmax thresholds of more than 3 to 5 °C compared to the reference seasonal normal over a period of at least three to six consecutive days (Frich *et al.*, 2002; see international projects or software designed to calculate these indices: CLIMDEX, STARDEX and ETCCDI);
- Relative Tmax thresholds based on values ≥ the 90th percentile (denoted Tmax90p or other reference percentile, Zacharias *et al.*, 2014) of the climatological reference value over a period of at least three to six days (Gachon *et al.*, 2005; Smith *et al.*, 2013).

For example, a recent study carried out in Germany (Zacharias *et al.*, 2014) analyzed the impact of heat waves on ischemic human heart disease vis-à-vis the mortality and morbidity observed during the period 2001–2010. It defines heat waves as periods of at least three consecutive days with an average daily temperature above the 97.5th percentile of the reference temperature distribution. In Canada, a study by Casati *et al.* (2013) used six indicators defining a heat wave with combinations of Tmin and/or Tmax (univariate or combined criterion of Tmin and Tmax) above fixed temperature thresholds (22–24 °C for Tmin and 30–35 °C for Tmax). These temperature thresholds were selected by Health Canada as empirical values known for their adverse effects on human health in Canadian communities (Casati *et al.*, 2013). Two other criteria based on Tmin or Tmax values (non-combined occurrence) were also used above the 95th reference percentile on an annual basis.

Appendix D (*Figure D.1*) shows the climatology for the 1981–2010 heat waves for Canada (south of 60°N) using the six definitions suggested above (Tmax ≥ 3, 5 °C or 90th percentile of the reference Tmax with durations of three or six or more consecutive days). As shown in this figure, occurrences of six days or more (either with absolute or relative thresholds) are climatologically rare in Canada, with usually less than one occurrence per year on average over the vast majority of regions. Moreover, even with shorter periods of three days or more, occurrences of Tmax sequences exceeding absolute thresholds (3 or 5 °C) or relative thresholds (Tmax90p) paint a highly varying picture from one region to another. For example, maritime regions or areas near large bodies of water (e.g., the Great Lakes, coastlines of the Hudson Bay, the Labrador Sea and the Pacific Ocean) generally show fewer occurrences compared to other sectors when Tmax absolute thresholds are used, but sometimes, higher occurrences when relative thresholds are used. This suggests that local physiographical factors greatly influence the occurrence, duration and severity of heat waves, that is to say, they modify in substantial manner the statistical distribution of the local temperature. That is why in the Canadian context more "flexible" definitions based on territory should be considered for heat waves, inasmuch as criteria or definitions used elsewhere in the world are difficult to use without adapting them to Canada's regional climates. The warm extremes of Tmax/Tmin are in fact very different from region to region across Canada, as the (day-to-day) intra-monthly variability is very high across the territory and is consistently higher in Eastern Canada (thus affecting the duration of heat waves), at least for Tmin from June to August and for Tmax in June/July (see *Appendix C*, *Figure C.2*).

4.1.b. Biometeorological indices

Among the various biometeorological indices that have been developed at the international and national level, most have been used to assess the risks related to health (Vaneckova *et al.*, 2011). Composite indices or biometeorological indicators have been used to evaluate heat-related human comfort and discomfort more accurately than temperature only. Some of the best-known biometeorological indicators are:

- The heat index (used by the NWS in the United States, for example; Rothfusz, 1990): Based on a multiple regression analysis, this index combines temperature and relative humidity data (Oleson *et al.*, 2015);
- Apparent temperature (Steadman, 1994): This index combines data on air temperature, water vapour partial pressure in the air, and wind speed at 10 m (Flatau *et al.*, 1992; Oleson *et al.*, 2010; D'Ippoliti *et al.*, 2010);
- The Simplified Wet Bulb Globe Temperature (Willett and Sherwood, 2012): This index combines data on air temperature and water vapour partial pressure in the air (plus an empirically defined constant);
- The humidex (Masterson and Richardson, 1979): This index also combines air temperature and water vapour partial pressure in the air (or specific humidity). The details of the calculation of this index, which is used regularly in Canada, are provided in *Appendix A*;
- The discomfort index (Epstein and Moran, 2006): This index also combines air and dew point temperatures (Stull, 2011);
- The Universal Thermal Climate Index (UTCI; Pappenberger *et al.*, 2015): This index was defined to include not only thermal factors (air temperature) but also health information on the human body's thermal equilibrium, human physiology and clothing. This index was developed using one of the most validated and advanced models in this field (Psikuta *et al.*, 2012) regarding heat transfer and human thermoregulation (Fiala *et al.*, 2001; Fiala *et al.*, 2012). This index was developed by a multidisciplinary team of experts as part of a commission of the International Society of Biometeorology (ISB) and the European COST Action 730 program (Cooperation in Science and Technology; Jendritzky *et al.*, 2009), under the aegis of the WMO–Commission for Climatology (CCI). It can be used for key applications in human biometeorology such as daily forecasts and warnings, urban management and land-use planning, environmental epidemiology and research on climate impacts. Moreover, this index applies to all types of climates (Pappenberger *et al.*, 2015).

The first five biometeorological indices listed above have been tested in the United States and in Canada (southern part). This was done in order to quantify – in the recent (1986–2005) and future (2046-2065) climate contexts – any possible manifestations of heat stress in urban and rural areas and, in particular, to look at the effects of urban density on heat stress (Oleson *et al.*, 2015). The usefulness of the UTCI index was demonstrated within the context of the probabilistic forecast for the 2010 heat wave in Russia (Pappenberger *et al.*, 2015). It was shown that probabilistic UTCI forecasts are superior in skill to deterministic (i.e. using one single weather model) forecasts and that despite global variations, the UTCI forecast is skilful for lead times up to 10 days (Pappenberger *et al.*, 2015).

In addition, several impact studies on human health have also used various definitions of biometeorological multivariable heat wave indices (e.g., HHWS, 2006, D'Ippoliti *et al.*, 2010; Martel *et al.*, 2010; Chebana *et al.*, 2013). In Québec for example, these last two studies have shown that a definition of threshold alerts based on a weighted average of three consecutive days of forecast Tmax and Tmin improves the monitoring system for heat-related deaths in different urban areas in southern Québec. In Europe, the D'Ippoliti *et al.* study (2010) also had the goal of producing a standard definition of heat wave in order to estimate the impact on mortality by gender, age and cause of death, using a combination of apparent temperatures (second index listed above) for both Tmax and Tmin. Among the nine European cities studied, this study clearly demonstrated the extent to which the effects of heat waves are highly heterogeneous geographically, as well as that mortality increases by more than three times (compared to the normal rate) during episodes of long duration and high intensity. In addition, this study showed that the most significant effects were observed in people with respiratory problems, especially for women aged 75 to 84 years.

In Australia, various composite biometeorological indices were examined to assess the sensitivity of links to mortality (Vaneckova *et al.*, 2011), such as apparent temperature, the heat stress index, the Thom discomfort index (Thom, 1959), the humidex and the dew point temperature. Hot days were defined as days when the observed values reached or surpassed the 95th percentile for each heat stress indicator (Vaneckova *et al.*, 2011). This study found that, regardless of the biometeorological index used or the measurements and temperature criteria used, mortality was greater on hot days than on other days (control values). In addition, this study shows that the effect of air pollutants (fine particulate ≥ 10 µm and ozone) seems discernible for some temperature indicators, and that the use of daily mean temperature performs similarly to composite indexes (Vaneckova *et al.*, 2011).

A recent study in France on the definition of temperature thresholds used for the health monitoring system during heat waves (Pascal *et al.*, 2013) evaluated various potential thresholds as percentiles associated with a significant mortality (percentiles corresponding to the inflection point in response to excess mortality), using the Tmax and Tmin averaged over three consecutive days. Among the six French cities studied, there was a strong correlation between the current thresholds and the thresholds derived from models, with a 0 °C to 3 °C difference for the Tmax averages. This study also showed that the use of different threshold values made it possible to anticipate the main periods of excess mortality during the summers of 1973 to 2003 (Pascal *et al.*, 2013).

In the United States, a recent study of heat waves (period of 1987–2000), based on 108 communities, showed that most excess mortalities are simply related to the independent effects of individual days of high temperatures (Gasparrini and Armstrong, 2011). An additional effect is superimposed during heat waves that last longer than four days.

4.2 2010 HEAT WAVE IN ONTARIO AND QUÉBEC

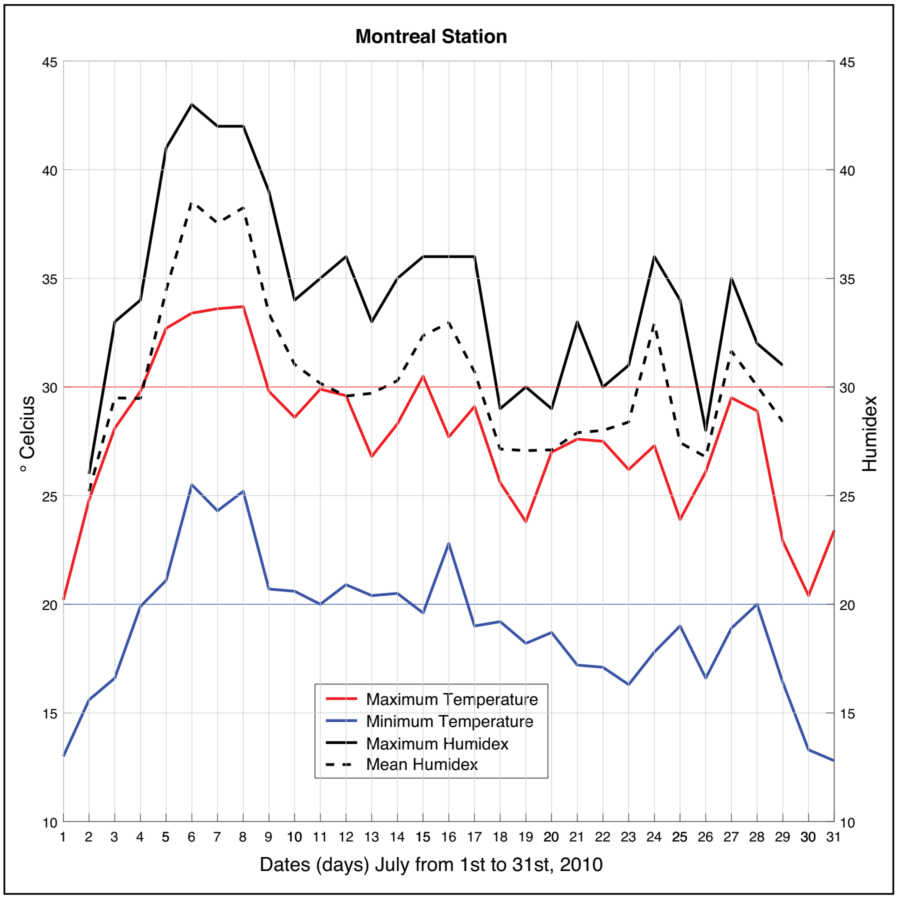
In the south of Québec and Ontario, July 2010 was marked by an unprecedented heat wave, rarely observed in recent decades (Bustinza *et al.*, 2013), that is why this event was selected here to examine its main characteristics. We will examine if this type of event could potentially increase in term of occurrence under warming conditions across Canada, using ensemble of regional climate model simulations available over the course of the 21st century.

The effects on human health of the heat wave that affected southern Québec and Ontario from July 5 to 10, 2010 are well documented: There was a 33% increase in mortality and a substantial increase in admissions in eight Québec health centres (Bustinza *et al.*, 2013). The Tmax in southern Québec and Ontario exceeded 33 °C for several days with humidex values of over 35 (*Figure 1*), even reaching 42 to 45 in some sectors of the St. Lawrence Valley and the Montérégie region during the hottest days (e.g., July 8, *Figure 2*). In addition, the Tmin stayed above 20 °C, in particular from July 5 to 8, 2010 in Toronto and until July 10 in Montréal (*Figure 1*). Thus, this heat wave was exceptional in terms of duration and intensity. As shown in *Figure 2*, this event affected the most densely populated valleys of Ontario and Québec, where the major cities and infrastructure of the two provinces are located. The St. Lawrence and Champlain/Richelieu River valleys with their predominantly north-south orientation (i.e., allowing warmer air and pollutants from the south to move in) and their local sources of air pollutants, have some of the highest smog frequency rates and ozone concentrations in Canada (see http://www.ec.gc.ca/Air/). These areas were the most affected by the highest number of deaths over all Québec health regions (RSS) analyzed (Bustinza *et al.*, 2013), with the highest Tmax (≥ 34 °C) and Tmin (≥ 24 °C), including those of Montréal, Outaouais and Montérégie. In these highly urbanized regions, the minimum temperature peaks were reached very rapidly, namely 24 hours after the start of the heat wave (July 4 in Outaouais, and July 5 in Montréal and Montérégie areas). As shown in other studies in the USA (Ramlow and Kuller, 1990; McGeehin and Mirabelli, 2001), the maximum value of the Tmin and the time to reach this peak are important factors in estimating the intensity of a heat wave and the severity of its (mortality and morbidity) impacts (e.g. Bustinza *et al.*, 2013).

By using the combined criteria of Tmin ≥ 20 °C, Tmax ≥ 33 °C and a humidex ≥ 40 for three consecutive days (thresholds similar to those proposed in *Table 2*, Section 3 or by the study on mortality/morbidity by Chebana *et al.*, 2013; see Section 6 and *Appendix E*, *Table E.1*, for RSS Class 3 used in Montréal and Montérégie areas), we can actually show that this heat wave was unusual in its extent and magnitude. Such series of three days or more, with high temperature and humidity (day/night), are rarely observed in the actual climate (not shown here; the climatology of heat waves using a combination of joint Tmin and Tmax over 3 days and more is presented in *Figure F.2*, *Appendix F*). As suggested in *Appendix F* (*Figure F.1*), the frequency of heat waves (May to September) of this type of event will increase, especially in the second half of the 21st century in southern Québec, Ontario, Manitoba and Saskatchewan, according to available regional projections (based on ensemble simulations of different regional climate models). Using the same combined thresholds of Tmax (≥ 33 °C), Tmin (≥ 20 °C) and humidex (≥ 40), we can expect the number of occurrences of these events to double by the end of the 21st century (according to RCP8.5 scenario, *Figure F.1 Appendix F*), that is, one or two events a year on average in the future climate. If we use certain indicators for picking up a milder signal (using for example combination of Tmax ≥ 31 °C and Tmin ≥ 16 °C thresholds as those applied in northern RSS areas, see *Appendix E*, *Table E.1*), a more pronounced extent of this type of heat wave will be potentially experienced across all regions of Canada under future climate conditions.

In summary, even if heat wave definitions oriented toward applications in the health field have been proposed, most of the studies confirm the importance of using thresholds in terms of Tmax and Tmin, as well as in terms of duration, which take into account the local weather and climatology (Laaïdi *et al.*, 2004; Chebana *et al.*, 2013). In addition, one must also consider socio-economic vulnerabilities of the populations concerned and their degree of exposure (IPCC, 2012; Bouwer, 2013). Several studies have effectively shown that thresholds used for warning systems can vary considerably from one city to another. In Canada, given the wide variety of climatological (and weather) conditions across the country, it is especially important to use flexible thresholds throughout the region. In Québec, such a surveillance and alert system with thresholds adapted to the regional climate of each sub-region of the province became operational in June 2010 (Toutant *et al.*, 2011), replacing uniform thresholds for all sectors in the province. In Ontario and Alberta, different thresholds adapted to climatic regions have been identified by MSC, in cooperation with local PHDs. The MSC is in the process of harmonizing its heat warnings with public authorities' extreme heat alerts in order to communicate risk to the public in a coherent fashion.

Figure 1. Tmax, Tmin and humidex (maximum and daily average) **observed for stations in Montréal (McTavish) and Toronto (Pearson) from July 1 to 31, 2010. These stations are part of ECCC's network of stations.**



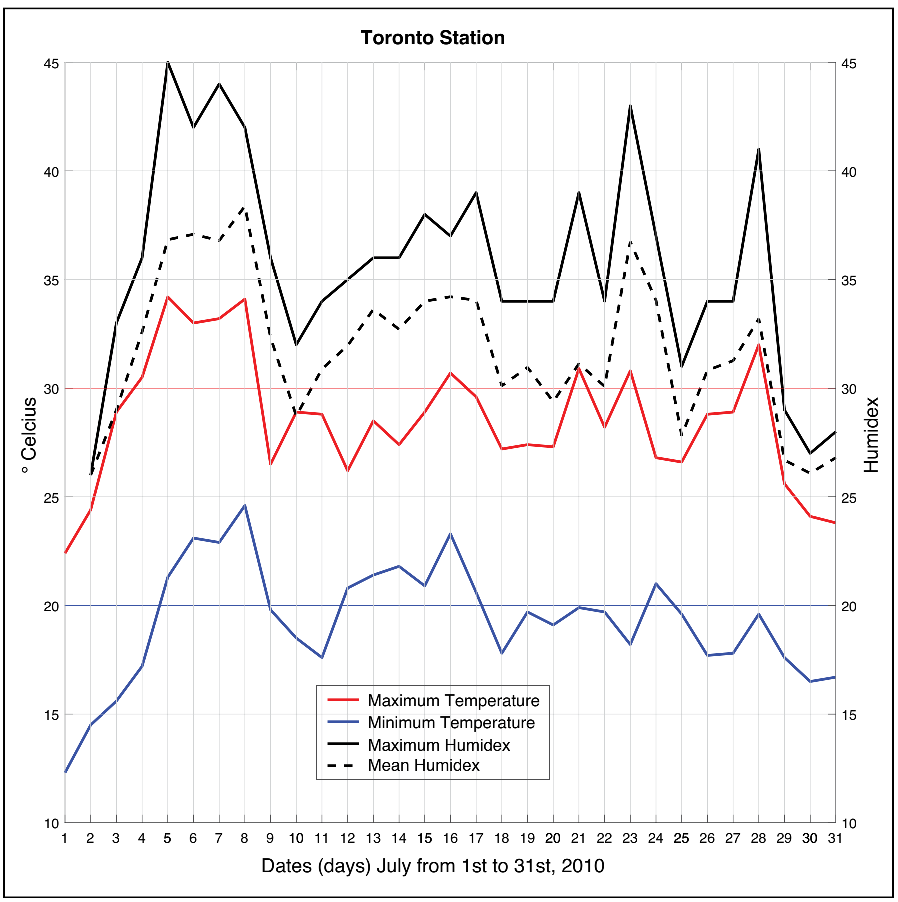
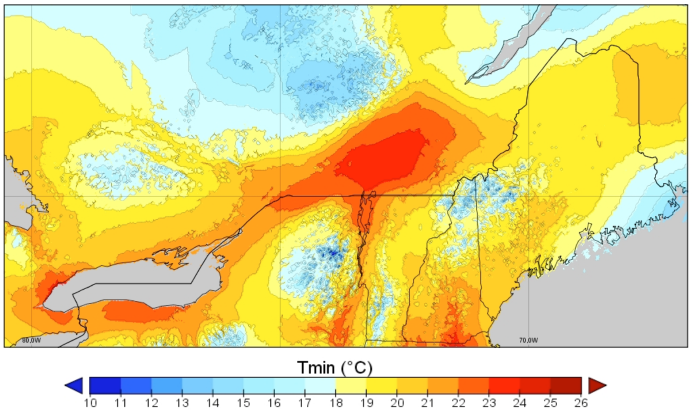
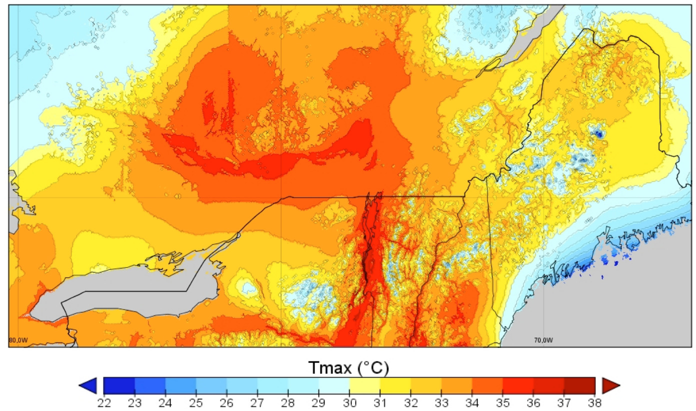


Figure 2. Values on July 8, 2010 in Southern Québec and Ontario for a) Tmin, b) Tmax and c) humidex. The humidex was calculated from the available variables (e.g., water vapour pressure and daily temperatures) from the Daymet database (Bristow and Campbell, 1984; Thornton *et al.*, 1997; Thornton and Running., 1999; Thornton *et al.*, 2014).

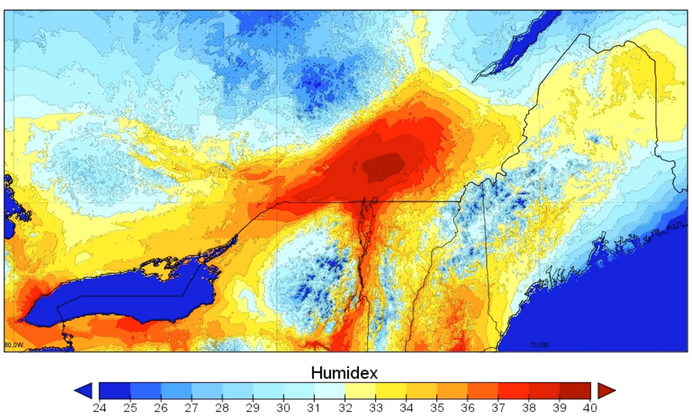
a) Minimum temperature on July 8, 2010



b) Maximum temperature on July 8, 2010



c) Humidex on July 8, 2010



Note: All values are derived from the Daymet database produced by NTSG (Numerical Terradynamic Simulation Group; http://www.ntsg.umt.edu/project/daymet) at a resolution of 1 km.

5. Predicting air temperature in urban and peri-urban zones

5.1 URBAN HEAT ISLAND (UHI) CONCEPT

Air temperature in urban areas may differ substantially from that in rural areas. This UHI effect is caused by surface materials (such as concrete, asphalt, etc.) storing heat during the day and releasing it throughout the night. Additionally, the Bowen[17] ratio, which is the ratio of sensible heat flux (heat conduction or convection from the surface to the atmosphere or vice versa) to latent heat flux (related to the evaporation of surface water), is about 0.2 in irrigated agricultural production areas, 0.5 in open grassy fields, and over 0.7 in urban areas[18] (Chapter 3, pp.74–75, Stull, 2015). This is directly related to the fact that vegetated surfaces are smaller and that the ground is more "artificially" waterproofed in urban areas than in the countryside, thus limiting water infiltration and the accumulation of water in the soil. This then creates the conditions for higher surface temperatures in the city than in the country (and higher values of sensible heat fluxes from the surface, which favor the heating of the overlying air), due to the lower evaporation rate from urban surfaces compared to natural surfaces. In the latter, the process of evaporation cools down the surface temperature and thus inhibits the overlying air temperature from increasing during the day (Oke, 1982 and 1997).

Some large cities (population over one million) report average annual temperatures of 1 °C to 2 °C warmer than the surrounding rural areas (Oke, 1997). On nights when the wind is calm and the sky is clear, the temperature difference can sometimes reach up to 12 °C (Oke, 1987). Even within cities, some neighbourhoods or areas may be hotter than their surroundings, creating intra-urban heat islands (IUHI). During the day, the situation is more complex (Bryson and Ross, 1972), and the temperature difference between urban and rural areas may be higher or lower (than during the night), depending on surface conditions and the meteorological context (Oke, 1997; Martin *et al.*, 2015).

17 The Bowen ratio (B) is defined by: $B = F_H / F_E$, where F_H is the sensible heat flux and F_E the latent heat flux. This ratio, used for the distribution of the relative portions of turbulent flows of heat and humidity, depends largely on the availability of surface humidity (see Oke, 1982; Stull, 2015).

18 This ratio is usually higher in the city than in the countryside, with values from 0.75 in Montréal and above 1 in Vancouver, as measured based on observed values obtained in these two cities (Yap and Oke, 1974; Oke and Fuggle, 1972; Oke, 1983).

5.2 LOCAL FACTORS EXACERBATING AIR TEMPERATURE IN CITIES

Several factors contribute to the change in temperature of the ambient air at the local level; some are natural or "uncontrollable" while others are caused by humans, and therefore "controllable" (Memon *et al.*, 2008).

The temperature at the local level is influenced chiefly by three natural (hence uncontrollable) factors:

1) Advection (horizontal), related to the transport of an air mass from one place to another, thus dependent on wind and the temperature and humidity of the air mass in question;

2) Turbulence, influencing heat and humidity sources and sinks from the surface to the atmosphere or vice versa;

3) Topography, responsible for downward/upward movement of air in mountainous areas or closed to mountainous areas; the latter is called the "foehn"[19] effect (compression by subsidence, or expansion by ascendance, of the air mass, causing it to warm or cool, respectively).

Uncontrollable factors, therefore, include meteorological parameters such as cloud cover, wind speed, sunlight conditions and precipitation, as well as natural surface conditions (all modifying the surface energetic budget and the air temperature over the surface).

Controllable factors include land use and anthropogenic changes made to the natural environment. They comprise industrial and other sources of heat, air pollutants, surface modified conditions, as presented above (UHI and IUHI), and the urban structure (geometry) of the city. For example, an "urban canyon" – a narrow street lined with tall buildings –

19 Air mass heated and dried by a downward movement, usually down the leeward side of a mountain. The air mass on the ascending side of the mountain (windward side) undergoes significant cooling as it rises, which increases its relative humidity until possible saturation. Any condensation will produce clouds or precipitation on the windward side of the mountain. Downstream from the mountain, the air descends again and is heated by compression, departing from its saturation point (the sky clears up and the rain on the leeward side of the mountain usually stops). Depending on the amount of water vapour lost in that process and the difference in altitude before and after the obstacle, the downstream temperature could be warmer than upstream.

affects wind circulation and can cause air to stagnate between the buildings, or conversely, cause the wind to blow stronger if it is blowing along the street. The canyon also influences the amount of solar radiation received during the day, as well as the portion of the infrared radiation re-emitted at night (Oke, 1982). In fact, streets that are boxed in between tall buildings receive less solar radiation, due to the buildings' shadowing effect, but on the other hand, the narrowness of the urban canyon prevents heat from dissipating upward.

At the MSC, different methods or strategies are used to predict the temperature at different spatial scales: regional (a few thousand km^2), local or urban (hundreds of km^2), or even at a finer resolution, intra-urban (tens of km^2 or less). This section identifies and explains two different approaches, with respect to forecasting the temperature at the urban and intra-urban scales: the geostatistical approach and the high-resolution numerical modeling approach.

5.3 GEOSTATISTICAL APPROACH

The geostatistical approach is used to determine first the spatial variability of temperatures in a city in retrospective mode (using observations to spatially reconstruct heat events) and then in forecast mode (using a geostatistical model developed from observations to predict temperatures in different areas of the city). This approach, based on temperature measurement campaigns, was tested in Montréal from data collected during the 2013 and 2014 summers.

5.4 TEMPERATURE-MEASUREMENT CAMPAIGNS

Historically, temperature forecasts for cities are based on temperatures observed at surrounding airports; that is, places usually located on the outskirts of cities and that for a long time have provided almost the only reliable source of weather information. These airports, which constitute reference stations, only rarely represent the actual temperature affecting the urban fabric.

For example, the temperature forecast for the Greater Montréal area is based on temperatures observed at the Pierre Elliott Trudeau International Airport, where the physical environment is quite different from that of downtown Montréal. Consequently, temperature thresholds that trigger a "heat wave plan alert" to be issued by health authorities or a heat warning by the MSC can be reached in certain areas, but not at the reference station.

As the current network of observation stations is generally not sufficiently dense in urban areas, the setting up of a temporary network of weather stations covering several areas of the city (during the peak heat wave season) is of considerable interest (Muller *et al.*, 2013).

Some studies have been aimed at quantifying the impact of UHIs on intra-urban temperature variability (e.g., Basara *et al.*, 2008 and 2010; Watkins *et al.*, 2002; Cheung, 2011; Bergeron, 2012). These measurement campaigns can help to generate databases that provide insight into space/time temperature variability as a function of different types of urban environments.

Moreover, these observational data may also be used in the development of geostatistical models for forecasting intra-urban temperatures or in the assessment of atmospheric numerical models at very high resolution, which will be discussed further. Due to the various physical environments that influence the spatial variability of temperature, observation sites should therefore represent as much as possible the different types of urban environment; for example, type of land use or summer growth of vegetation.

In the urban environment, it is virtually impossible for most observation sites to comply with WMO standards (for example, the clearance around the sensors). A guide prepared for the WMO by Oke (2006) provides recommendations for obtaining representative meteorological observations at urban sites. The MSC therefore opted for realistic criteria regarding clearance around buildings, and made sure that the immediate environment surrounding the sensors (or probes) was relatively consistent.

In short, an in situ measurement at a fine spatial scale campaign makes it possible to observe the evolution of temperature in various environments and urban neighborhoods. There are techniques for extending and fine-tuning this information for the entire territory of interest; for example, via the geostatistical or urban modeling approaches described below.

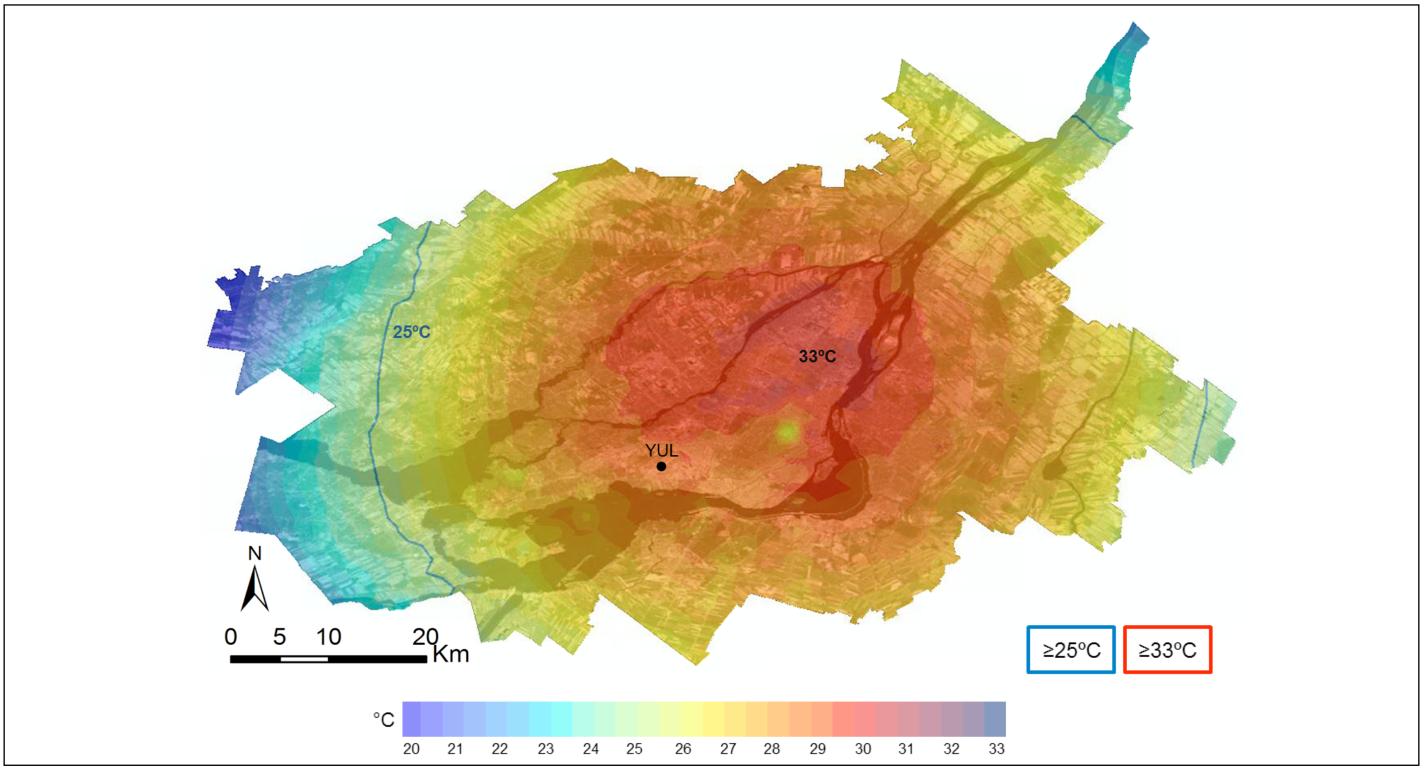
5.4.a. Case study: Measurement campaigns in Montréal (2013 & 2014)

The MSC conducted two summertime temperature-measurement campaigns in various parts of Montréal in 2013 and 2014. The purpose of these campaigns was to quantify the differences between the temperature observed in various urban environments and the temperature measured at the reference station (Pierre Elliott Trudeau International Airport). About 30 observation sites were chosen specifically to closely represent the different physical environments found in the city.

Measurements taken in Montréal during the summer of 2013 revealed that temperature observed at night is generally higher downtown, and that in residential areas temperature depends on the vegetation amount. Differences between Tmax recorded at the majority of sites within the city (IUHI) and those observed at Pierre Elliott Trudeau International Airport can reach up to 2 °C during a heat wave. However, the largest differences usually occur at night (up to 4 °C).

The information derived from observations was combined with other geophysical variables or related to the land use plan (topography, vegetation amount, urban structure, etc.) to spatialize the temperature at Montréal through an interpolation method (kriging, or co-kriging, method, by taking surface covariates into consideration). *Figure 3* shows an example of this approach to reconstruct the spatial distribution of air temperature in Greater Montréal area during a heat wave (in July 2013), in retrospective mode.

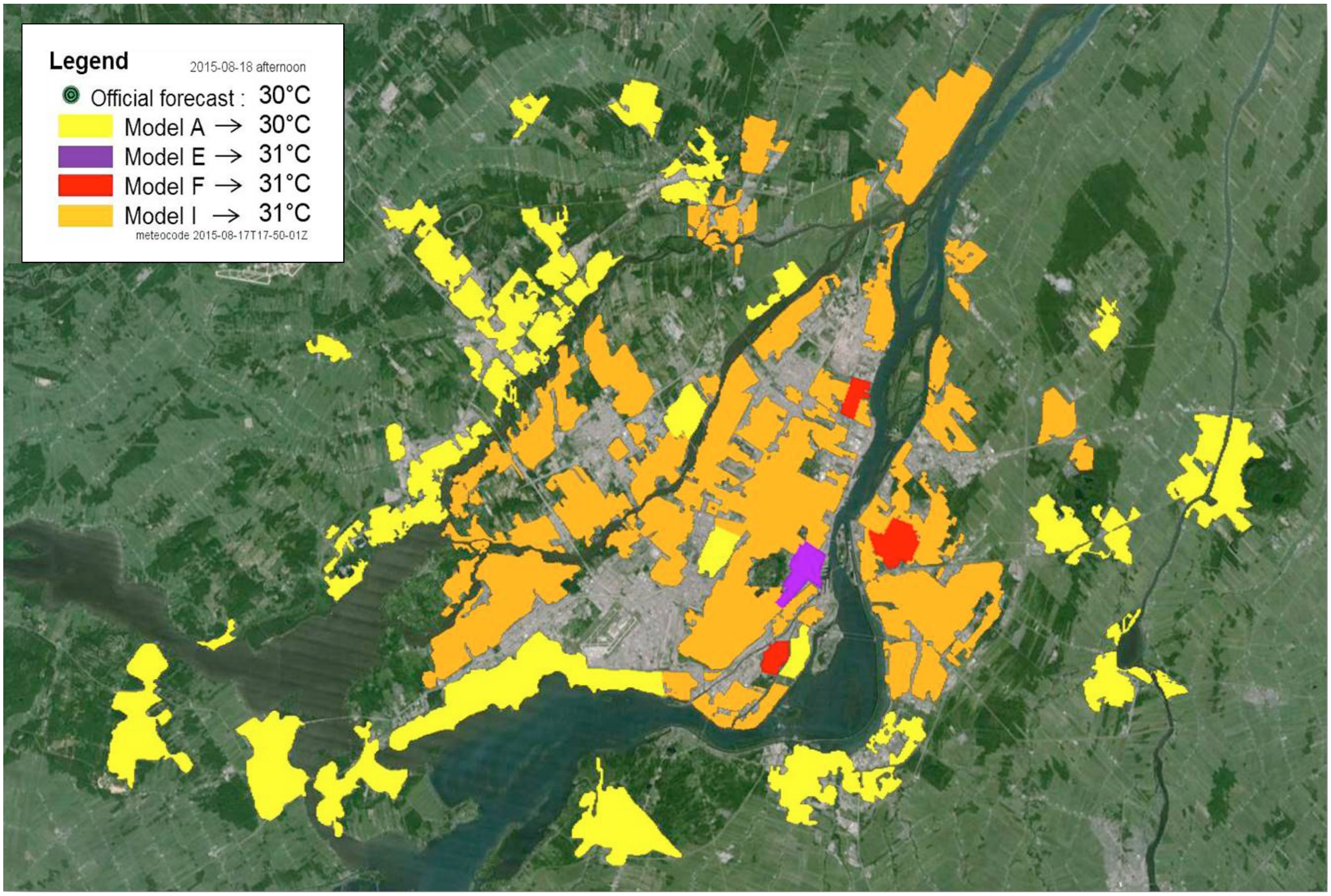
Figure 3. Spatial distribution of air temperature (in °C) in Greater Montréal on July 16, 2013, 21:00 (local time) geostatistical approach). YUL corresponds to the location of the Pierre Elliott Trudeau International Airport station.



The measurement campaigns carried out in Montréal also led to the development of a forecasting-mode model (multivariate regression model), incorporating weather information related to surface conditions, in order to represent the thermal behaviour of the entire urban area during a heat wave. It was then possible to analyze the relation between surface conditions and weather conditions in greater depth. This analysis led to the development of a model for estimating temperature differences between various neighbourhoods and the reference station.

This model was also used in forecast mode in order to predict the temperature in certain areas of Greater Montréal. On July 16, 2013, the forecast Tmax (at the airport) was 31 °C. According to the geostatistical approach, sectors having both similar vegetation ratios and similar urban structures were grouped into various zones (see *Figure 4*, Models A, E, F and I) with different expected Tmax. In *Figure 4*, the same hot areas are observed on Montréal and Laval islands, as well as on the south shore (Longueuil/Brossard), as those shown in *Figure 3*. This model, while promising, needs to undergo further validation. This geostatistical approach, after validation by *in situ* observations, will provide valuable information in forecast mode.

Figure 4. Spatial distribution of air temperature (in °C) on July 16, 2013 for certain areas of Greater Montréal (forecast mode).



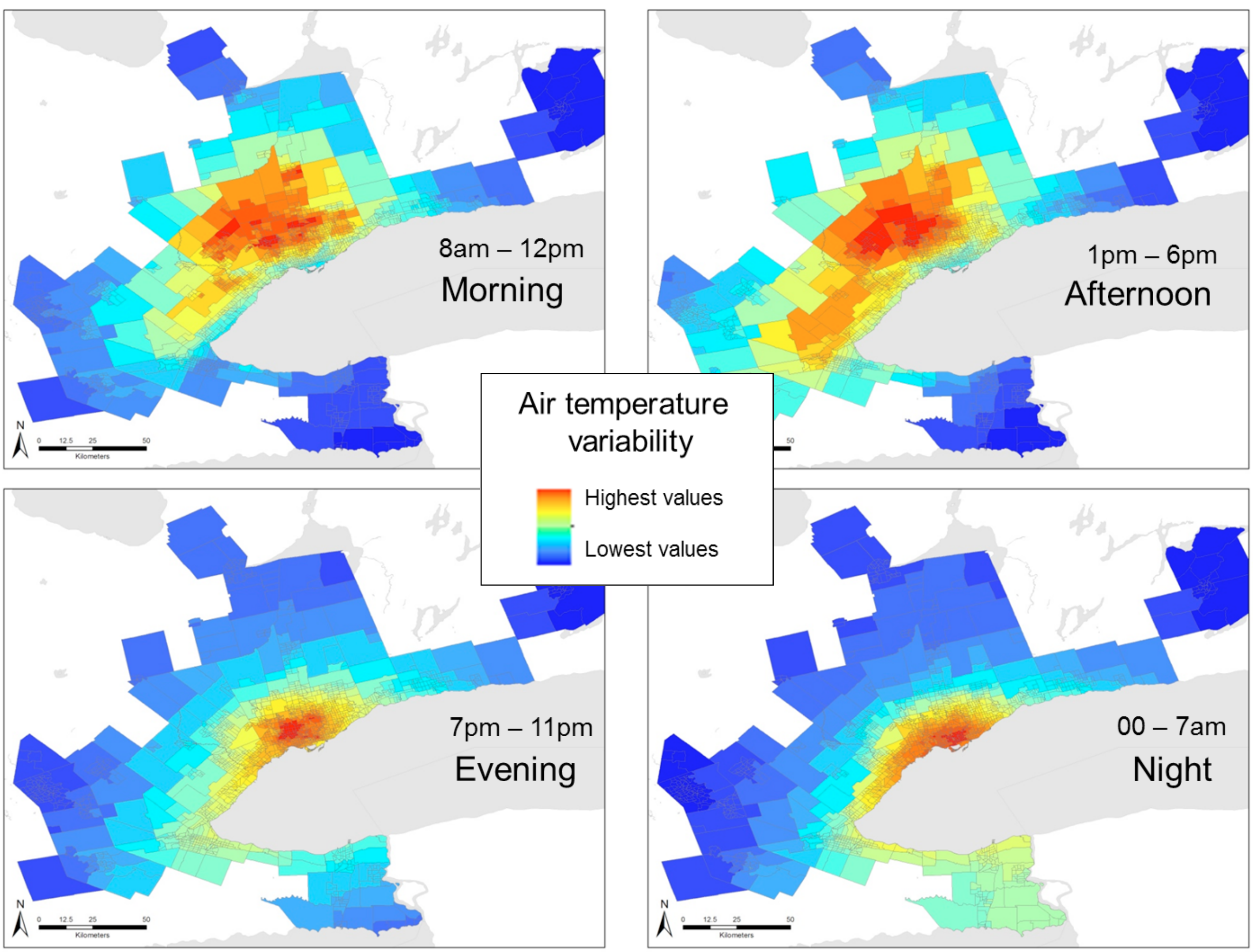
5.4.b. Case study: The evolution of the heat dome in Greater Toronto on July 16, 2013

The same exercise was conducted in Greater Toronto by using networks of official stations already installed, as well as in some private station networks (e.g., *Wunderground*), for lack of targeted measurement campaigns. For Toronto, only the spatial reconstruction of heat events has ever been achieved up to now. The lack of reliable data from targeted campaigns currently limits the development of a geostatistical model in forecast mode for this city.

This study assessed how heat is distributed in Greater Toronto during a heat wave, while an anticyclone helps a breeze to develop off Lake Ontario. The lake breeze develops on sunny days, producing a wind that blows from the lake to the shore, due to the increase in temperature difference between the water's surface (cooler) and the earth's surface (warmer) during the day.

Figure 5 shows the heat dome over downtown Toronto, on the shore of Lake Ontario. Gradually, as the day progresses (08:00 to 18:00 local time), the heat dome is displaced northward by the lake breeze that develops and cools the immediate vicinity of the lake. By late afternoon, the lake breeze fades and disappears, allowing the heat to resettle over downtown in the evening (19:00 to 23:00 local time) and overnight (00:00 to 07:00 local time).

Figure 5. Spatial distribution of hourly temperature in Toronto from July 16, 2013, 08:00 to July 17, 2013, 07:00 (local time).



5.5 URBAN NUMERICAL MODELING AT HIGH-RESOLUTION

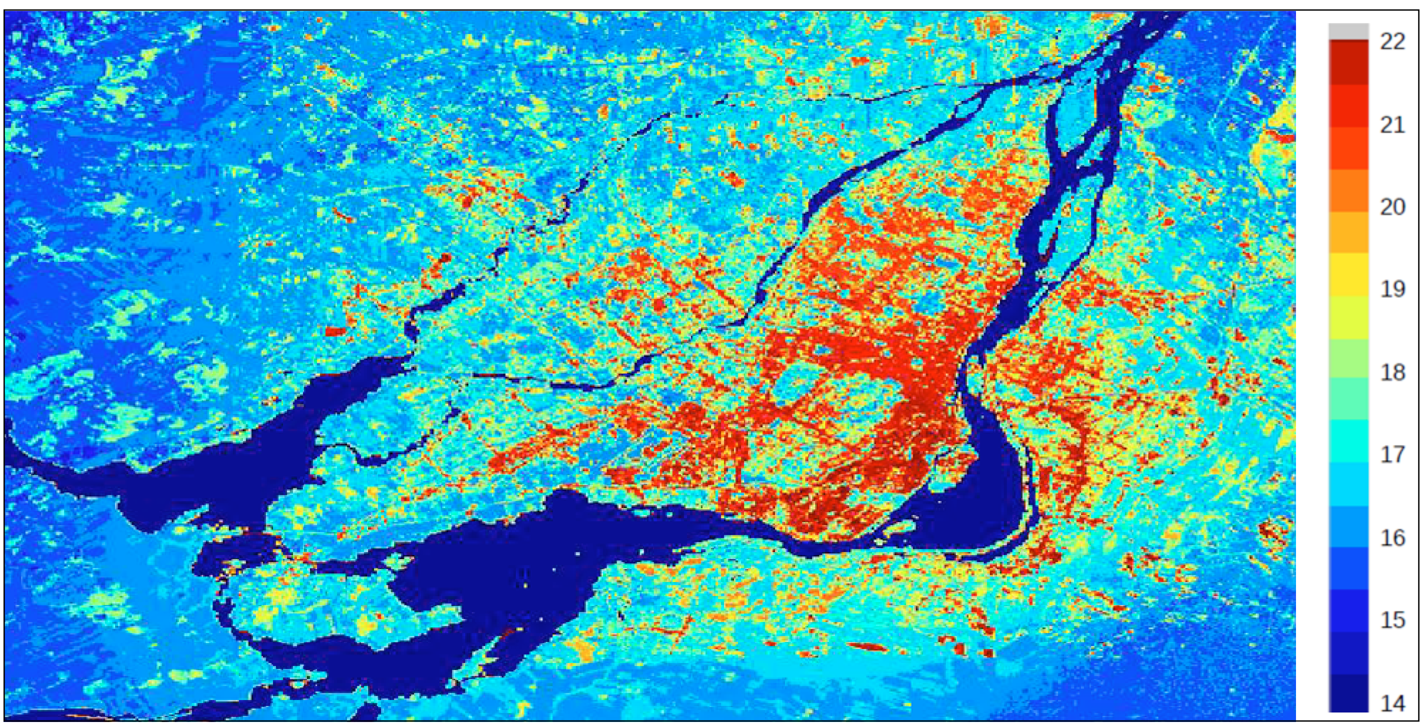
All the major weather centres worldwide issue forecasts based on numerical models. ECCC has developed its own models, for different time scales, and at different resolutions (spatial scales). The models currently used at the MSC are the Regional Deterministic Prediction System (RDPS), for forecasts up to two days, at a 10 km resolution and the Global Deterministic Prediction System (GDPS), for up to ten days, at a 25 km resolution. A finer resolution model (high-resolution deterministic prediction system, HRDPS), at a 2.5 km resolution, is now available and will be soon implemented throughout Canada. The RDPS is being updated four times a day while the GDPS and the HRDPS are currently updated twice a day. Analyzing and forecasting the weather, using numerical models, requires an impressive amount of computing and data processing power. In addition, the finer the resolution, the more computer power is requested by the models.

In this perspective, models with a spatial resolution fine enough to capture the different environments within a city require huge computer capacity and cannot cover an entire country, especially a country as large as Canada. Not only the processing capacity of the computers would have to be gigantic, but also the time required to analyze and produce data would be too long to be of any use for short-term forecasts.

Nevertheless, ECCC continues to develop a very high-resolution urban (and intra-urban) numerical modeling system (1 km and 250 m) in order to improve forecasts for Canadian major cities (Leroyer *et al.*, 2014). At the same time, ECCC is developing another urban modeling system with still higher resolution (120 m). The latter simulates the conditions near the surface ("downscaling"[20] technique), based on meteorological information from models with lower resolution (*Figure 6*, source: Leroyer *et al.*, 2011). The air temperature over a city can be simulated using this modeling system, thus identifying the hottest sectors.

20 A (dynamical) downscaling method uses regional or local weather models of higher resolution than the global models from which they are produced.

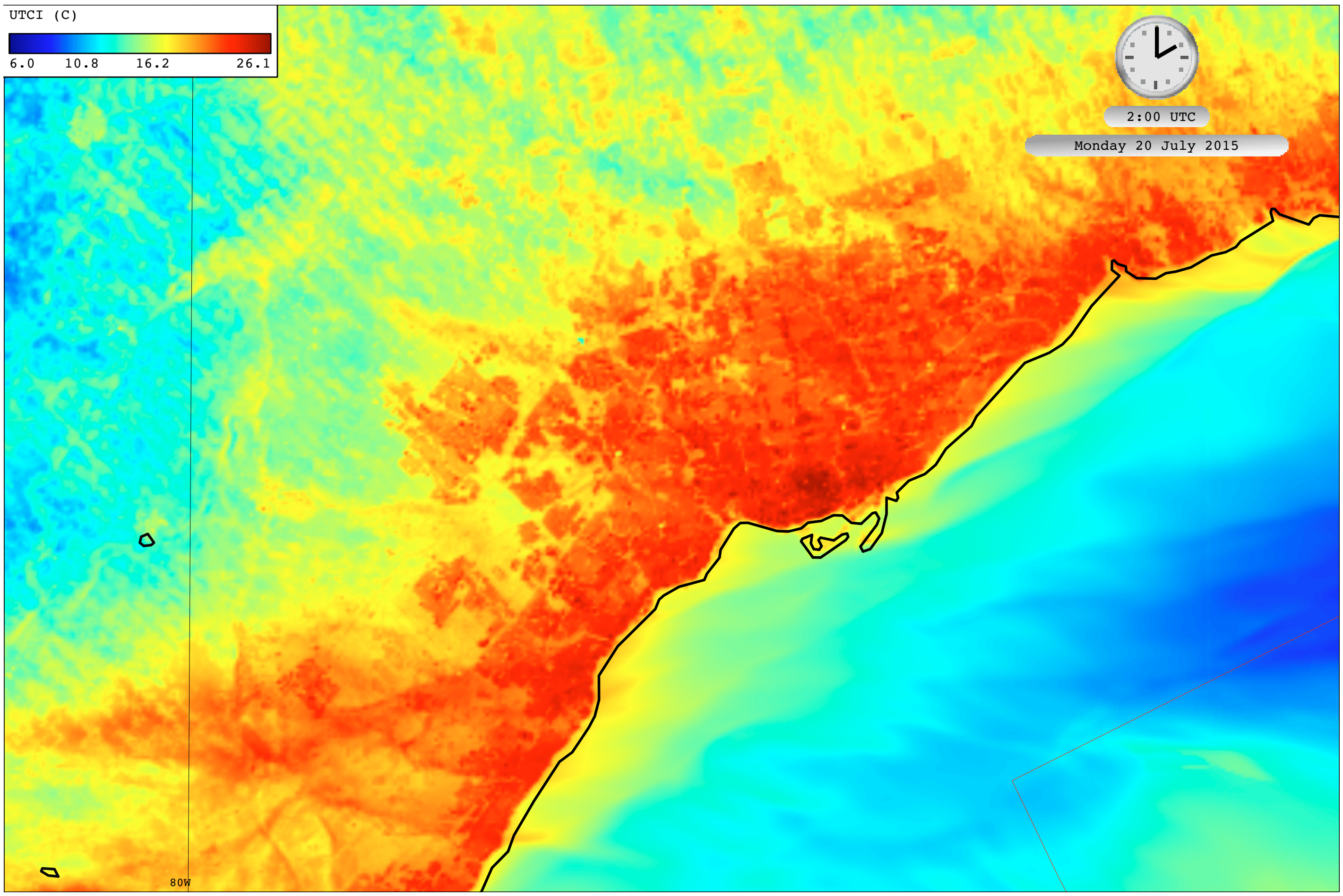
Figure 6. Simulation of air temperature (at 2 m, in °C) at 120 m resolution over Greater Montréal on July 6, 2008 at 11:00 (local time).



One of the benefits from this type of urban modeling can be the calculation of various indices of thermal comfort; for example, the biometeorological index UTCI presented in Section 4, as shown in *Figure* 7 for the Greater Toronto, at high resolution (250 m) (source: Leroyer and Bélair, 2014).

In summary, in the context of identifying heat wave alert thresholds for urban centres, such models (geostatistical and numerical tools) can be very useful as they provide detailed information in space and in time.

Figure 7. UTCI simulation at a resolution of 250 m for the Greater Toronto.



(Source: Leroyer, personal communication)

Although the methods presented here (geostatistical approach and high-resolution modeling) both allow spatializing or regionalizing temperature at the urban and intra-urban scale, they each have their limitations/advantages, as described briefly in *Table 5*.

TABLE 5. Comparison between the geostatistical approach and high-resolution modeling.

HIGH-RESOLUTION NUMERICAL MODELING	GEOSTATISTICAL APPROACH
Designed for large urban centres	Can be performed anywhere
Results plausible but not yet validated through observations	Based on the principle that the thermal behaviour of the urban canopy is included in the observations
Dynamic model outputs (varying as a function of inputs), which may reflect the evolution of a city, in near real time, or in projection mode by using urbanization scenarios	Results validated by measurements and applied in forecast mode Static results: The spatial differences between the values generated and the reference station are considered to be constant
Requires infrastructure and significant IT resources	Requires only a geographic information system (GIS)
Spatial resolutions of 120 m, 250 m and 1 km	Spatial resolution varies across the district

6. Considerations for thresholds identification

A heat wave alert system must be able to anticipate heat waves that are likely to have a significant impact on health so that public health decision makers have time to set up appropriate preventive measures. Most of these warning systems are based on monitoring a weather parameter (or a combination of several parameters, as suggested in Section 4) to assess the risk of reaching some thresholds during a given period. Identifying thresholds remains essential in developing an early warning system.

Several steps are necessary for identifying these thresholds: 1) Identifying meteorological parameters for measuring heat exposure; 2) Identifying health indicators for measuring the impact of heat on health; 3) Identifying vulnerable groups; and 4) Analyzing the link between health indicators and meteorological parameters.

6.1 IDENTIFYING METEOROLOGICAL PARAMETERS

The meteorological parameters (measurement of individuals' exposure to heat and thermal stress factors through some Tmax, Tmin and humidity thresholds) were identified in the previous sections (Sections 3 and 4), to which pollution thresholds may be added. To identify the most appropriate meteorological parameters and determine exposure to heat, the information (observations and forecasts) should be available on a daily basis and forecasts must be as accurate as possible (see Section 3). In Quebec, the SUPREME (see *Appendix B*) monitoring system uses Tmax and Tmin as meteorological parameters as they are not only available on a daily basis, but also because their forecasts are considered very accurate (see Section 3, *Table 3*). However, even though thresholds for air humidity have been determined (Chebana *et al.*, 2013), the SUPREME system does not use this parameter in the decision to send or not a heat wave alert because humidex forecasts are available (and reliable) only up to 48 hours. Nevertheless, the humidity information is regularly sent with every alert, as this can be used by decision makers to modulate the public health response.

6.2 IDENTIFYING HEALTH INDICATORS

Several health indicators have been shown adequate to measure the impacts of heat on health. Heat waves exert stress on the social and environmental determinants of health as well, and as mentioned above, have an impact on mortality, morbidity and well-being. For example, in Australia, the consequences of heat waves would represent an annual economic burden of approximately $6.2 billion (US), mainly because of the loss of productivity (reduced performance at work and at school, and absenteeism; Zander, 2015). In Québec, over the last six years (2010–2015), 14 of the 16 administrative regions covered by the SUPREME system were affected by at least one extreme heat wave (as defined in Section 2). In addition, significant increases in either daily death rates, or emergency admissions and ambulance transports were observed (Bustinza and Lebel, 2012; Bustinza *et al.*, 2014; Bustinza *et al.*, 2013; Lebel and Bustinza, 2013; Bustinza *et al.*, 2015).

Several heat-related health indicators have been identified in a literature review (Tairou *et al.*, 2010), which can be used to define the health effects of heat waves; and in particular, to ensure adequate preparation for public-health decision makers so they can monitor health conditions and their environmental determinants (e.g., hydrometeorological hazards) and ultimately prevent or reduce health damage.

Various causes of heat-related morbidity have been highlighted in the literature; however, the most commonly used health indicator remains all-cause **mortality** (Anderson and Bell, 2009; Basu and Samet, 2002). In Québec, during the heat wave that affected a large part of the province in July 2010 (see Section 4), significant increases in crude all-cause mortality rates (up to 36%) were observed in three out of eight administrative regions affected by the heat wave (Bustinza *et al.*, 2013), in very urbanized regions. It is well known that statistical power to detect a significant impact highly depends on the number of health events observed. Therefore, the less populated regions with a limited number of daily health events often show no significant impact on all-cause mortality due to lack of statistical power. The effects on mortality may occur immediately after the beginning of the heat wave, but they also appear up to three days after the end of the heat wave (all-cause mortality) and up to fifteen days for mortality from respiratory diseases (Ledrans and Isnard, 2003; Gasparrini *et al.*, 2015). Time is then a very important factor for the monitoring and surveillance of the health effects of heat. Overall, the all-cause mortality indicator seems to be sufficiently sensitive and specific as daily variations in deaths clearly reflect daily fluctuations in temperatures during a heat wave (Lebel and Bustinza, 2013). It is also available on a real or near-real time basis and measures adequately the impact of heat on health, which is an important consideration for surveillance purposes.

The number of all-cause **hospitalizations** is the second indicator (after deaths) most commonly used to analyze the impacts of heat waves on health. However, studies using this indicator are few and their conclusions differ. Some found that heat waves have caused significant increases in hospitalizations, whatever the causes, from 2 to 11% (Semenza *et al.*, 1999; Jones *et al.*, 1982), but three recent studies did not find any significant increases (Nitschke *et al.*, 2007; Nitschke *et al.*, 2011; Kovats *et al.*, 2004). In Québec, from 2010 to 2015, no significant effect on the crude rate of all-cause hospitalizations was noted during the heat waves that hit the province (Bustinza and Lebel, 2012; Bustinza *et al.*, 2013; Lebel and Bustinza, 2013; Bustinza *et al.*, 2014; Bustinza *et al.*, 2015, Lebel *et al.*, 2016). To explain this apparent lack of correlation between heat waves and hospitalizations, it has been postulated that extreme heat would cause cardiovascular deaths to occur very quickly, before patients can get in hospitals (Mastrangelo *et al.*, 2006; Diaz *et al.*, 2006; Kovats *et al.*, 2004). At present, there is no known heat alert system worldwide using thresholds obtained from all-cause hospitalizations data.

In regard to **ambulance transports** (a third potential health indicator), significant increases from 4% to 16% during heat waves have been observed in Australia and Canada (Nitschke *et al.*, 2007; Nitschke *et al.*, 2011; Dolney and Sheridan, 2006). It is interesting to note that this indicator is an alternative indicator for health impacts surveillance during heat waves when mortality data are not readily available, or in administrative regions having a low daily number of deaths. In Québec, five of the ten administrative regions that experienced extreme heat waves during the summers of 2012 and 2013 showed a significant increase in ambulance transports (around 15%) during these episodes (Lebel and Bustinza, 2013; Bustinza *et al.*, 2014); this included smaller and less urbanized regions as well as larger urban ones. As for the all-cause hospitalizations indicator, there is no known heat alert system using thresholds obtained from ambulance transports numbers. However, using the ambulance transports indicator to monitor heat wave impacts seems promising as their daily variations appear to reflect those in temperature (Dolnet and Sheridan, 2006; Nitschke *et al.*, 2011) and it is generally available in real or near-real time.

Finally, studies concerning the impact of heat waves on **emergency rooms visits** (ERV) show mixed results worldwide. In a recent study in Southern Ontario, ERV increased in some areas and not in others, up to 11% during a heat wave (Bishop-Williams *et al.*, 2015). In the United States, during the 2012 heat wave in Baltimore, no significant differences were observed for such visits and heat related weather variables (Levy *et al.*, 2015). Other studies report similar negative results (Sun *et al.*, 2014; Schaffer *et al.*, 2012). While emergency room visits do not qualify as an adequate indicator for a warning system, they could prove useful for decision makers to adjust the public health response during a heat wave, as they are often available in real time.

6.3 IDENTIFYING VULNERABLE GROUPS

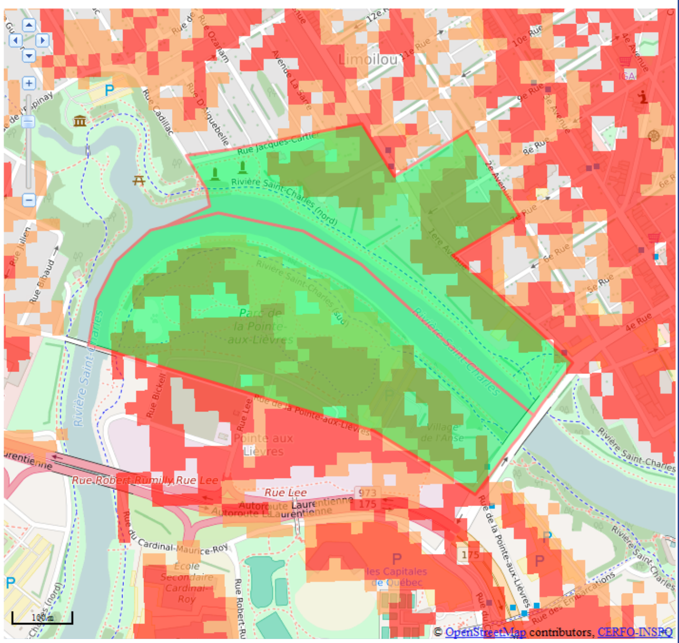
Another group of potential indicators, related to **living environment**, relates to specificities of large urban centres. This factor would be responsible for higher all-cause mortality during heat waves than when people live in small towns or the countryside (Jones *et al.*, 1982). One of the causes of this excess mortality is the UHI (see Section 5), generated by pavement surfaces, the large volume of infrastructure, and population density (Haines *et al.*, 2006; Kovats and Hajat, 2008; Luber and McGeehin, 2008). Also, living in an old building (possibly poorly insulated or decrepit) or in a small apartment, often poorly ventilated, has been linked to the deaths of those 65 years and older during the 2003 heat wave in France (Vandentorren *et al.*, 2006). Some studies have highlighted excess mortality during heat waves in people who are underprivileged and less educated (Basu and Samet, 2002; Kovats and Hajat, 2008; Curriero *et al.*, 2002; O'Neill, 2003) as well as perceived excess morbidity and high consumption of medical consultations (Bélanger *et al.*, 2015a) related to the housing and the neighbourhood.

Although the impacts on health affect all **age groups**, some vulnerable people are more at risk than others (D'Ippoliti *et al.*, 2010; Hajat and Kovats, 2008): For example, the elderly, children, people with chronic diseases and tradespeople working outdoors who are exposed to meteorological hazards (WHO, 2008). Although children under five have been identified as a risk group (Ledrans and Isnard, 2003), this risk is relatively low in industrialized countries (CDC, 2002). Last, **pre-existing chronic health problems** such as cardiovascular, respiratory and mental illnesses were also mentioned as a risk factor of the health impact of heat (Kovats and Hajat, 2008; Bouchama *et al.*, 2007; Kaiser *et al.*, 2001). In fact, a review of epidemiological studies on the effects of hot weather on public health in many parts of the world (Kovats and Hajat, 2008) confirms that while mortality from heat waves is more pronounced in the elderly, other groups may also be at higher risk (young children or adults with chronic diseases).

In 2014, the INSPQ produced heat vulnerability maps for all the Québec administrative regions based on indicators mentioned above and using the SUPREME system (see *Box 3*) mapping tool. These maps identify census dissemination areas[21] that meet certain heat vulnerability criteria. This information and the local teams' knowledge of the terrain can help locate groups that are vulnerable to heat and thereby prioritize interventions. One of the 12 vulnerability maps for the Québec City region is shown in *Figure 8*. In this figure, the indicators used are **heat islands**, number of people aged **65 and older**, density of people suffering **chronic diseases (based on hospital data)**, index of **material deprivation** and level of **air conditioning** (estimated from electric power use in summer).

Figure 8. Map of vulnerability to heat for part of the Québec City region.

Health Region 03
HEAT: Locations of vulnerable groups
Map 3: Québec City, Québec City Region, 1st Avenue and 8th Street



(Source: SUPREME, May 2014)

Green area surrounded by red: Dissemination areas having:
- a number fo persons aged 65 and over living alone equal to or greater than the 90th percentile;
- a "high" or "very high" density of persons suffering from chronic illnesses;
- a "very disadvantaged" population (materially and socially); and
- a "weak" or "very weak" level of air conditioning.

Red areas: "Very warm" heat islands

Orange areas: "Warm" heat islands

6.4 ANALYZING THE LINK BETWEEN HEALTH INDICATORS AND METEOROLOGICAL PARAMETERS

As mentioned above, the time between exposure to heat and death can be quite brief, hence the importance of establishing a monitoring and early warning system during hot weather, based on the weather forecast. In the wake of several heat waves around the globe, many warning systems have been developed to prevent deaths related to such events. In general, these systems are based on the establishment of thresholds for significant meteorological parameters, usually temperature or indices derived from them (as discussed in Sections 2, 3 and 4), which result in significant excess mortality (Ledrans and Isnard, 2003; Nicholls *et al.*, 2008).

The analysis of the links between health indicators and the meteorological parameters is based on identifying thresholds above which a heat wave might lead to a particular health problem to occur with significantly excessive frequency. To determine what constitutes a significant impact on health, the frequency of the health problem during the period when certain thresholds are exceeded (heat waves) are compared with periods of not exceeding it (control periods). Thus, two types of threshold causing a significant increase in the frequency of a health problem are determined: 1) The threshold value of the meteorological parameter, and 2) The threshold duration of this threshold value (Litvak *et al.*, 2005; Chebana *et al.*, 2013). In addition, some criteria are needed to adequately analyze this link: 1) The analyzed geographical unit must be uniform from the climate point of view, 2) Historical trends of the indicators used must be adjusted, 3) Health excesses must be specific to heat waves, and 4) The analysis of the links must take into account the lag time between exposure and the beginning of impacts.

In Québec, specific extreme-heat thresholds for each administrative region (listed in *Appendix E*, *Table E.1*) were established by the INRS (Institut National de la Recherche Scientifique, centre Eau-Terre-Environnement) and the INSPQ in 2009 using available weather and health information for the period of 1981 to 2005 (Chebana *et al.*, 2013). To define these thresholds, it was necessary to consolidate some administrative regions in order to have homogeneous classes from a climate perspective as well as a sufficiently high number of daily deaths for analysis. Research is currently underway to examine novel statistical methods that could better perform in such situations of low daily numbers. In addition, the temperature thresholds are using weighted averages to account for the uncertainties inherent in all forecasts (see Section 3, *Table 3*). These temperature thresholds result in a significant mortality excess (≥ 60%, which is the statistically detectable level for Québec), warranting a health alert trigger. Reference weather stations were also identified for each administrative region in order to monitor their general weather conditions.

21 A dissemination area is the smallest geographic region (400 to 700 inhabitants on average) for which all Canadian census data are distributed (https://www12.statcan.gc.ca/census-recensement/2011/ref/dict/geo021-eng.cfm).

BOX 3. The heat warning system in Québec.

SUPREME SYSTEM

In Québec, the INSPQ implanted the SUPREME system (shown in *Appendix B*) in 2010 (Toutant *et al.*, 2011; Bustinza *et al.*, 2011). During heat waves, this system automatically sends extreme-heat warnings, depending on the weather region[22], to public-health authorities, municipalities and emergency management, when the weighted averages of the expected temperatures for the upcoming days reach extreme heat thresholds, as shown in *Table E.1 of Appendix E*.

The SUPREME system is also being used to integrate different sources of information, and it offers a range of useful information and indicators for future interventions in various regions and ministries. Among the components of the system, we find daily information in near real time on some health indicators (deaths, hospitalizations, emergency admissions, ambulance transports, etc.), sociodemographic (population density, income, proportion of immigrants, etc.), environmental (urban heat islands, air pollution), in addition to weather forecasts and alerts (temperature, precipitation, ice storms, etc.) issued by ECCC.

PERFORMANCE OF THE WARNING SYSTEM

To analyze the reliability of extreme heat warnings, the INSPQ is currently studying the quality of the forecasts used to detect periods of extreme heat. However, assessing the quality of predictions of low base-rate extreme weather events is complicated by the fact that traditional performance measures of forecast quality typically degenerate to trivial values (tends to zero) as the rarity of the predicted event increases (Ferro and Stephenson, 2011). To verify the forecasts of the SUPREME system, the INSPQ has thus used the Symmetric Extremal Dependence Index (SEDI) proposed by Ferro and Stephenson; this measure is non-degenerating and base-rate independent. SEDI describes the association between forecast and observed rare events; the index has a fixed range between -1 to 1, where 0 indicates no skill and 1 a perfect score.

To determine whether a warning correctly predicted periods of extreme heat, the dates that the warnings were issued are compared with the start dates of extreme-heat periods. A warning is considered “correct” if issued at least two days before the start of a period of extreme heat and no later than the day it starts; all other warnings are classified as “wrong.” A period of extreme heat is identified when the average maximum and minimum temperatures observed at the reference stations in the weather regions reach the extreme heat thresholds (see *Table E.1*, *Appendix E*) for two or three consecutive days (two days for some administrative regions and three days for others).

Between 2010 and 2015, for all ECCC weather regions in Quebec, the SUPREME system issued 77 extreme-heat alerts based on ECCC forecasts, 44 of which were “correct,” and 33 “wrong,” while 93 periods of extreme heat actually happened. The ability of the SUPREME system to detect periods of extreme heat based on forecasts obtains a very good SEDI score of 0.83 with a standard error of 0.03; this indicates a very good association between forecasts and observed extreme heat periods. Besides, the false-alarm rate is 43% (33 wrong alerts out of 77 issued)[23].

Evaluations conducted on the system show that those in charge of the administrative regions seem satisfied with this performance. The uncertainty inherent to weather forecasts (89% success rate on day 3 of the temperature forecast in the summer, with a margin of error of ± 3 °C) leads us to some reservation with regard to the optimal FAR that can be achieved, at least in the context of the Canadian climate. In fact, the high spatial and temporal variability of temperatures over the Canadian territory (*Figures C.1* and *C.2, Appendix C*), constitutes an additional challenge for forecasters. In summary, the SUPREME warning system, based on forecasts and alerts issued by ECCC (and our risk-based thresholds), makes it possible for public health authorities to monitor and issue alerts in a timely manner.

22 A weather region is a geographical unit of homogeneous meteorological perspective designed and built by Environment and Climate Change Canada.

23 Bustinza and Gosselin, INSPQ, personal communication, October 2016; publication upcoming in 2017.

In conclusion, the identification of appropriate thresholds is an essential step in establishing a warning system. A heat wave monitoring system must be able to issue an alert when a period of hot weather that has the potential to have a significant impact on health is imminent. Two steps are important to establish such a system: selecting weather and health indicators, and analyzing the links between these two parameters. Choosing proper weather and health indicators requires that their relationship be firmly established in epidemiological studies, the data be available on a daily basis and the weather forecasts be as accurate or reliable as possible. Last, for a proper analysis, the geographical unit must be climatologically uniform, historical trends must be adjusted, the health impact must be specific to heat waves, and, when analyzing the links, the time between exposure (beginning of the heat wave) and the onset of health impacts must be taken into account.

Québec PHDs have used an operational definition of extreme heat wave since 2010. The SUPREME system sends warnings when two- or three-day temperature forecasts are expected to reach certain thresholds. The purpose of these warnings is to give PHDs enough time to implement prevention measures, therefore protecting the public’s health.

7. Summary and authors' recommendations

The negative effects on health caused by extreme heat events in Canada will intensify in the future, due mostly to the likely increase in frequency, intensity and duration of heat waves in the context of climate change (IPCC, 2013), while the aging population increases and the UHI effect is expected to grow due to increasing urbanization. More efforts are needed to reach a national approach focused on regional concerns (e.g., warning systems adapted to local needs), that would include quantifying the risks related to heat wave occurrences, taking into account factors such as health, socio-economic and environmental vulnerability (e.g., chronic diseases, changing demographics, urban densification, living environment, etc.). Mitigation and adaptation efforts (e.g., green roofs, increase of vegetated surfaces in cities, etc.) must also be taken into consideration, as they can help in reducing UHIs and IUHIs and their exacerbating effects on ambient heat.

In this context, the following recommendations follow:

- First, adopt a standard terminology and use a common vocabulary (MSC, health authorities, research, etc.) in order to facilitate the exchange of information and interpretation arising from weather/climate conditions and their impact on health;
- Identify different thresholds according to climatic regions: The MSC should adjust its heat warning thresholds to those defined by provincial health authorities (through epidemiological studies), according to local conditions. For example, different MSC thresholds should be defined for Sept-Îles vs Montréal, as was done for Thunder Bay vs Toronto (see *Table 2*); those thresholds also need to be reevaluated on a regular basis, taking into account the most recent data (health, climate, NWP models);
- Identify appropriate thresholds in Nunavut and other northern areas/arctic territories. The physiological adaptation in northern communities is not the same as for people living farther south, and continuous sunshine in summer result in relatively high Tmin. The precarious socio-economic and living conditions of these populations also add to their vulnerability. For the moment these thresholds are difficult to define, due to the scarcity of heat events and the low number of people exposed, making it difficult to get significant epidemiologic studies; in the meantime, warning thresholds based on climatology (e.g., Tmax $\geq$ Tmax90p), and a basic heat action plan should at the very least be put in place;
- Define "flexible" thresholds according to the time or period of the year: For example, a heat wave in May can have more impact than the same conditions in July, as the body is less likely to have had time to acclimatize to the heat during the spring;
- Issue early (timely) notifications for triggering efficient heat-health action plans in vulnerable populations, especially in urban and peri-urban areas; in general, the synoptic signature of severe and extensive heat waves is identifiable up to a week in advance. Advance-notice weather forecasts, including uncertainties, should be issued for public-health authorities and other partners;
- Develop effectiveness indicators for mitigation measures that reflect the ultimate goal, which is to reduce excess mortality and morbidity among populations;
- In a more systematic manner, evaluate and verify predicted temperatures versus values measured over regions, rather than at stations (point values) that are not necessarily representative of broad geographic areas. The forecasts and the information for health authorities should include local effects within climate regions, leading to differences in temperature by several degrees (plus or minus). The variability of nighttime temperatures must also be better represented in the warnings and/or information transmitted;
- If necessary, use more complete biometeorological indices (such as the UTCI) if the required information is available (see Section 5, *Figure* 7).

With respect to data accessibility and integrating the various sources of information (meteorological and health) when monitoring conditions and issuing warnings, it is recommended to:

- Facilitate access to and optimize the use of weather information at high spatial and temporal resolution (daily or even hourly data), including public and private observation networks, and take advantage of products that are in the experimental or developmental phase (e.g., Daymet high-resolution data; see *Figure 2*);

- Continuously monitor and analyze weather and health conditions in urban and peri-urban areas, given that:
  - An increasing number of heat waves could lead to an increase in urban mortality, as shown in many studies, particularly in 2003 in Europe and 2010 in Québec.
  - The exacerbation of warming in urban areas (UHI and IUHI) will also affect residential needs for cooling or air conditioning systems (increased summer energy demand).
- Anticipate the growing need for weather and climate information in the surrounding urban and peri-urban areas to provide baseline data on a regular basis.

Of course, heat-related mortality can occur even at temperatures below established thresholds. Appropriate prevention is necessary, even when the warning criteria are not met (as suggested by recent works by Pascal al., 2013). Moreover, communicating risks, broadcasting advice on adaptive behaviour, and community support must be set up before and during heat waves. During such events, parameters other than temperature, for example humidity, air pollution, social events or even health-data monitoring, should not only be available but also utilized by health authorities when making decisions, interventions or warnings.

In addition to defining thresholds (in collaboration with health authorities), MSC should continue its work in outreach and education with stakeholders (including media), policy makers and the general population, to help them better understand the warning system, and which preventive actions should be taken. Adaptation to heat also includes individual behaviour that can be measured and tracked over time; a first heat adaptation index has also been proposed for urban areas (Bélanger *et al.*, 2015b) for this purpose.

There is certainly a need for more research regarding adaptation and acclimatization of the population, in order to update warning systems on a regular basis. Effective action plans and warning systems offer hope in addressing future challenges on health issues related to climate change. In addition, strategic priorities should include further modeling work at the urban level and measurement campaigns in large urban centres (in order to refine IUHI identification). Lastly, similar work is needed with respect to cold weather, which is also responsible for a significant number of deaths, globally and nationally.

The population's demographic and socioeconomic characteristics such as age, income, living environment, education and health conditions in general affect heat-related mortality. In this perspective, it would be important to assess the potential impact of recurrent and severe heat waves in the future according to demographic projections available (no doubt to be developed) in Canada (as suggested by a recent study in the United States by Jones *et al.*, 2015). Subsequent analyzes regarding exposure to extreme weather conditions will benefit from the continued improvement in spatial projections taking into account the continued aging of our population, as well as high-resolution weather forecasts and climate projections. For this to happen, a concerted collaborative effort among several institutions as well as a diversity of expertise will be required.

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Appendixes

Appendix A. Humidex definition and calculation

The humidex is a Canadian innovation, first used in 1965 and developed at Environment and Climate Change Canada by Masterson and Richardson (1979). It was designed by Canadian meteorologists to describe how hot, humid weather is experienced or perceived by a normal person. The humidex combines temperature and humidity into one value (no unit) to reflect the temperature as perceived by human beings. Because it takes into account the two most important factors affecting humans' comfort or degree of discomfort in the summer, it may be a better measurement of how the air becomes "stifling" or is felt as such by the human body than it is by considering the temperature or the humidity alone.

Using the partial pressure of water vapour, we can calculate the daily value of the humidex using the following formula:

$$Humidex\ (H) = T + 5/9(e - 10)$$

With, T the (average) temperature of the air in degrees Celsius and e the partial vapour pressure of the water vapour in hPa. The average daily temperature (T value) is calculated from the minimum and maximum daily temperatures (Tmin and Tmax, respectively):

$$T = \frac{Tmax + Tmin}{2}$$

If the partial pressure of steam is not available (as measured direct or simulated variable), it can be calculated using the relative humidity HR and the saturation vapour pressure of the air $esat$, using the equation:

$$e = \left(\frac{HR}{100}\right) \times esat$$

A polynomial approximation can be used to calculate the saturation vapour pressure (as suggested by Lowe, 1977). The air temperature T must be between -50 °C and +50 °C to use this approximation in the following formula:

$$esat = a0 + T\times\left(a1 + T\times\left(a2 + T\times\left(a3 + T\times\left(a4 + T\times\left(a5 + T\times a6\right)\right)\right)\right)\right)$$

With,

$$a0 = 6.107799961$$
$$a1 = 4.436518521\times10^{-1}$$
$$a2 = 1.428945805\times10^{-2}$$
$$a3 = 2.650648471\times10^{-4}$$
$$a4 = 3.031240396\times10^{-6}$$
$$a5 = 2.034080948\times10^{-8}$$
$$a6 = 6.136820929\times10^{-11}$$

The humidex is used widely in Canada. However, extremely high humidex values are rare except in areas of southern Ontario, Manitoba and Québec. In general, the humidex decreases with latitude. Of all Canadian cities, Windsor (Ontario) had the highest recorded humidex measurement of 52.1 on June 20, 1953 (Source: Environnement Canada, 2015). The warm, humid air masses that cause these high humidex values come mostly from the Gulf of Mexico or the Caribbean (www.ec.gc.ca/meteo-weather, *search Humidex table*). In *Table A.1* below, humidex values are given as a function of the values of relative humidity and air temperature. According to these values, degrees of discomfort vary according to established thresholds (the values according to the colour codes used in *Table A.1*).

TABLE A.1. Range of humidex values according to relative humidity and temperature values, and degree of associated comfort

HUMIDEX AND DEGREE OF COMFORT – LEGEND

Humidex	Degree of Comfort
20 – 29	No discomfort
30 – 39	Some discomfort
40 – 45	Great discomfort; avoid exertion
46 and over	Dangerous; possible heat stroke

HUMIDEX FOR RELATIVE HUMIDITY FROM 100% TO 65%
Refer to legend above.

Temperature (°C) / Relative Humidity	100%	95%	90%	85%	80%	75%	70%	65%
21 °C	29	29	28	27	27	26	26	24
22 °C	31	29	29	28	28	27	26	26
23 °C	33	32	32	31	30	29	28	27
24 °C	35	34	33	33	32	31	30	29
25 °C	37	36	35	34	33	33	32	31
26 °C	39	38	37	36	35	34	33	34
27 °C	41	40	39	38	37	36	35	34
28 °C	43	42	41	41	39	38	37	36
29 °C	46	45	44	43	42	41	39	38
30 °C	48	47	46	44	43	42	41	40
31 °C	50	59	48	46	45	44	43	41
32 °C	52	51	50	49	47	46	45	43
33 °C	55	54	52	51	50	48	47	46
34 °C	58	57	55	53	52	51	49	48
35 °C		58	57	56	54	52	51	49
36 °C			58	57	56	54	53	51
37 °C					58	57	55	53
38 °C							57	56

Source: www.ec.gc.ca/meteo-weather, *search Humidex table.*

Appendix B. The SUPREME system (SUrveillance and PRevention of Extreme Meteorological Events)

CONTEXT

Public health officials need access to reliable and timely information in order to trigger an intervention in case of an extreme weather event. The PHD must promptly make decisions based on a range of information that are not always readily available and that come from several sources. In a needs analysis in 2009, the DSPs expressed an interest in having a central system for the information they need to make informed decisions when it came time to trigger measures for preventing the impacts related to extreme weather events.

OBJECTIVES

The objectives of the system are:

- Producing leading-edge knowledge for assessing the effects of extreme weather events on public health;
- Making readily available a reliable and constantly updated source of information for decision makers to use when making informed intervention decisions during extreme weather events;
- Limiting the effects of extreme weather events on public health. Improving the monitoring of extreme weather events should reduce disease, injury, death and psychosocial problems related to such events. For example, our public health objective is that excess deaths in an affected area should not exceed 30% of the historical mortality rates of similar periods during the years previous to the heat wave; and that
- Closer collaboration with key partners be encouraged to make improvements to the monitoring system.

THE SYSTEM

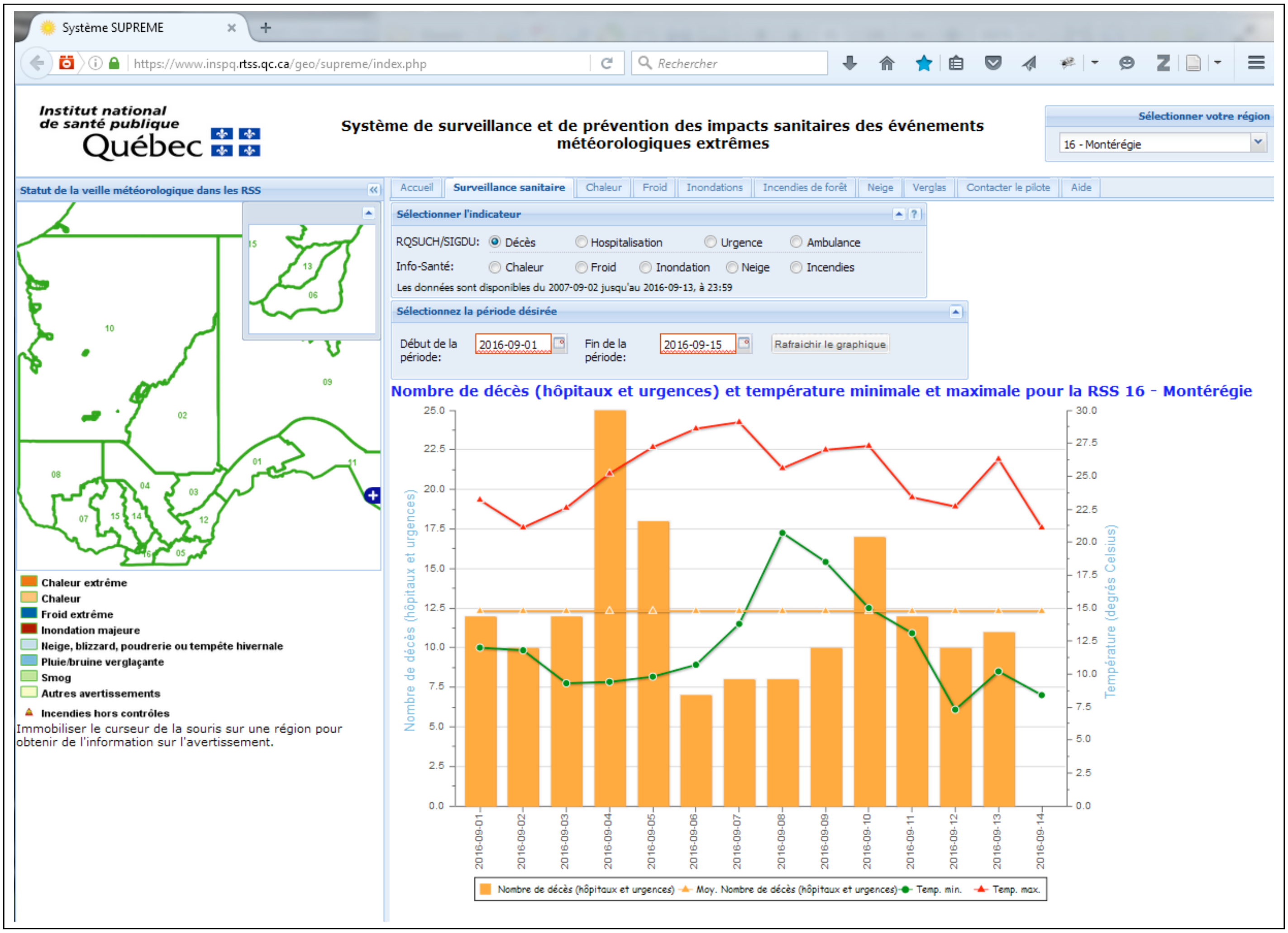
The SUPREME system portal contains information and indicators that may be useful to regional and departmental respondents for future interventions. SUPREME was developed using advanced open-source or free software with a substantial development community (Bustinza *et al.*, 2011; Toutant and al., 2011). In addition, the available data are provided by multiple sources: various provincial and federal ministries, government organizations, crown corporations and more. SUPREME uses web services that query directly where the data reside. This way, each retain ownership of their data and is responsible for updating, providing free access to its partners. The map-based data are configured to facilitate a rapid response time.

Implemented in May 2010, SUPREME provides access to several indicators regarding:

- <u>Exposure to hazards</u> (temperature, heat island, humidity, rainfall, active forest fires, fire danger rating, areas at risk of flooding, flooded areas, concentration of pollutants in the air, etc.);
- <u>Socio-economic neighbourhood characteristics</u> (population density, Deprivation Index, housing conditions, degree of air conditioning, location of swimming pools, air-conditioned shelters, temporary housing in the event of disaster, day-care centres, health facilities, low-cost housing and so forth);
- <u>Health problems</u> (death, emergency admissions, hospitalizations, ambulance transports, chronic multimorbidity index, consumption of health services); and
- <u>Monitoring the situation by field teams during and after the intervention</u>.

Several of these indicators are available in real or near real time, including health indicators at the regional level and observed temperatures (*Figure B.1*).

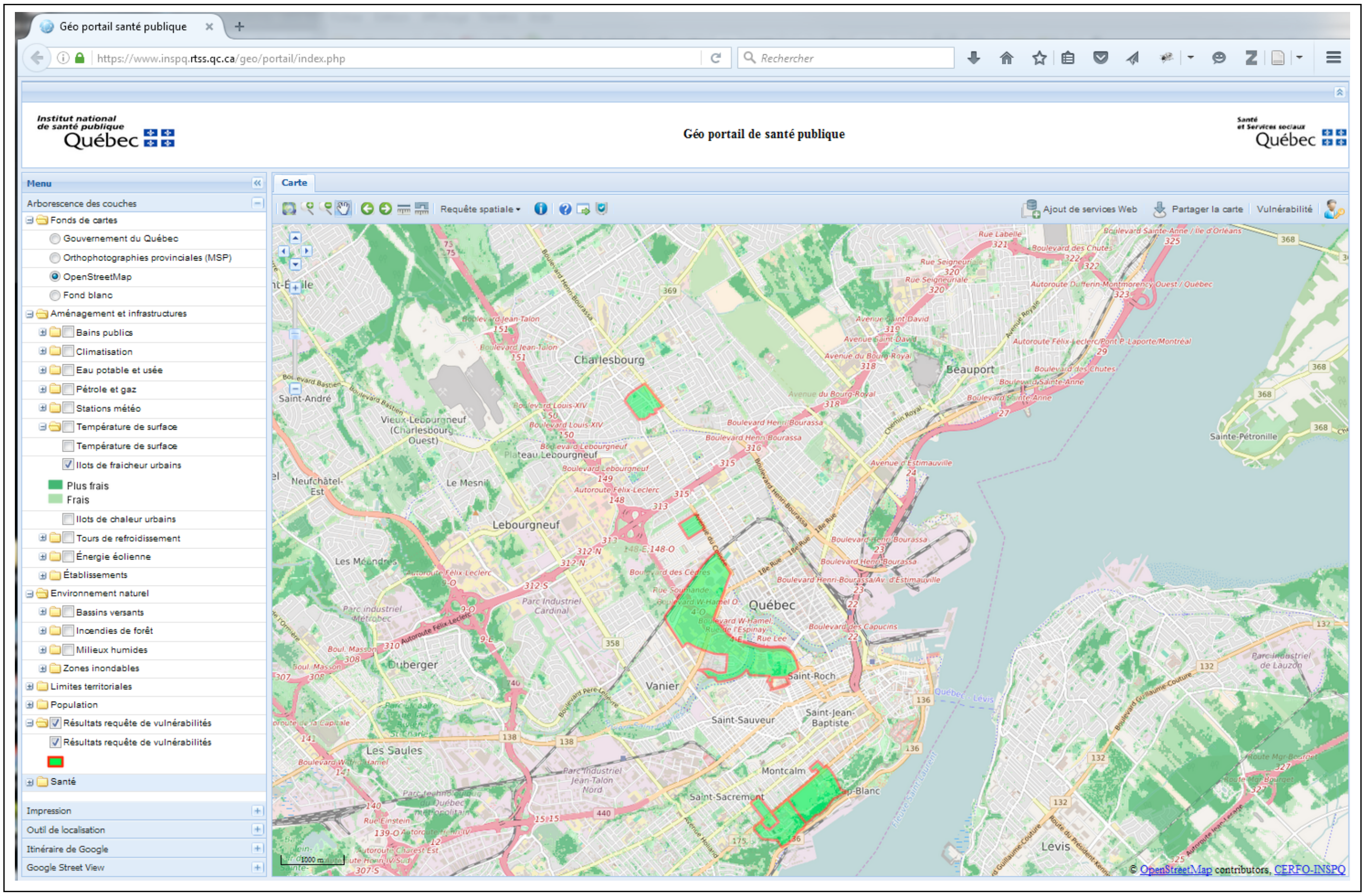
Figure B.1. The "SUPREME system's "Health monitoring" tab.



SUPREME users who request it can receive automated warnings regarding extreme heat, extreme cold, major floods, heavy snow, freezing rain, smog and so forth, 24 hours a day, 7 days a week, by email when certain thresholds are reached.

Furthermore, the SUPREME mapping application can be used to make vulnerability requests for a given hazard (*Figure B.2*) by configuring indicators to target the census dissemination area (unit of 400-700 people, on average).

Figure B.2. Example of a vulnerability mapping application request.



A user group was created to orient the system, to propose adjustments, and to approve modifications. The groupe is mainly composed of representatives of the regional teams on environmental health and of the MSSS, civil protection professionals and of the INSPQ. Constant interaction with the MSC and the MSP are also part of the process, and adaptations are made progressively with the evolution of the information systems of our partners.

Since 2011, twice has the SUPREME system been evaluated by users. Globally, SUPREME is considered a valuable tool and is much appreciated. In Quebec, the system currently represents the only common source of relevant information at the provincial level for diverse extreme meteorological hazards. It regroups, in a central location, rigorous and reliable information, while providing knowledge on the state of the situation in other regions when inter-regional coordination is necessary.

Appendix C. Climatology (1981–2010) of monthly minimum, maximum and average daily temperatures and their intra-monthly standard deviations (June, July and August)

Figure C.1 Climatology of the monthly average for the period 1981–2010 in Tmin (left panels) and Tmax (centre panels) and Tavr (right panels) for the months of June, July and August (panels from top to bottom, respectively). Daily data used are provided on a Lambert conformal conic projection with a resolution of 5 minutes of arc (≈10-km) and developed in grid format using data from Environment and Climate Change Canada observation stations by Dr. Dan McKenney of the Canadian Forest Service (Natural Resources Canada; details provided in Hutchinson *et al.*, 2009; Hopkinson *et al.*, 2011; McKenney *et al.*, 2011).

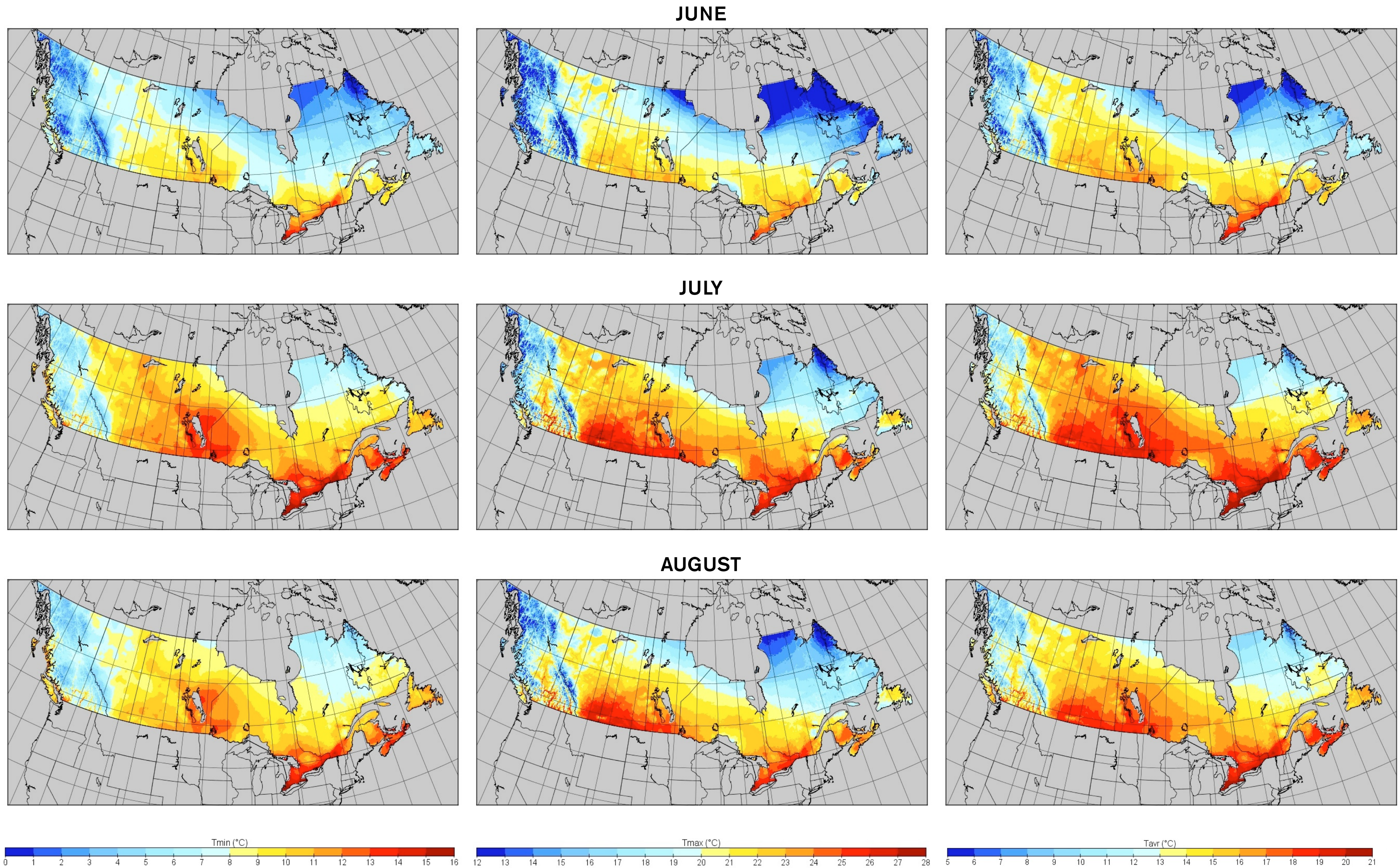
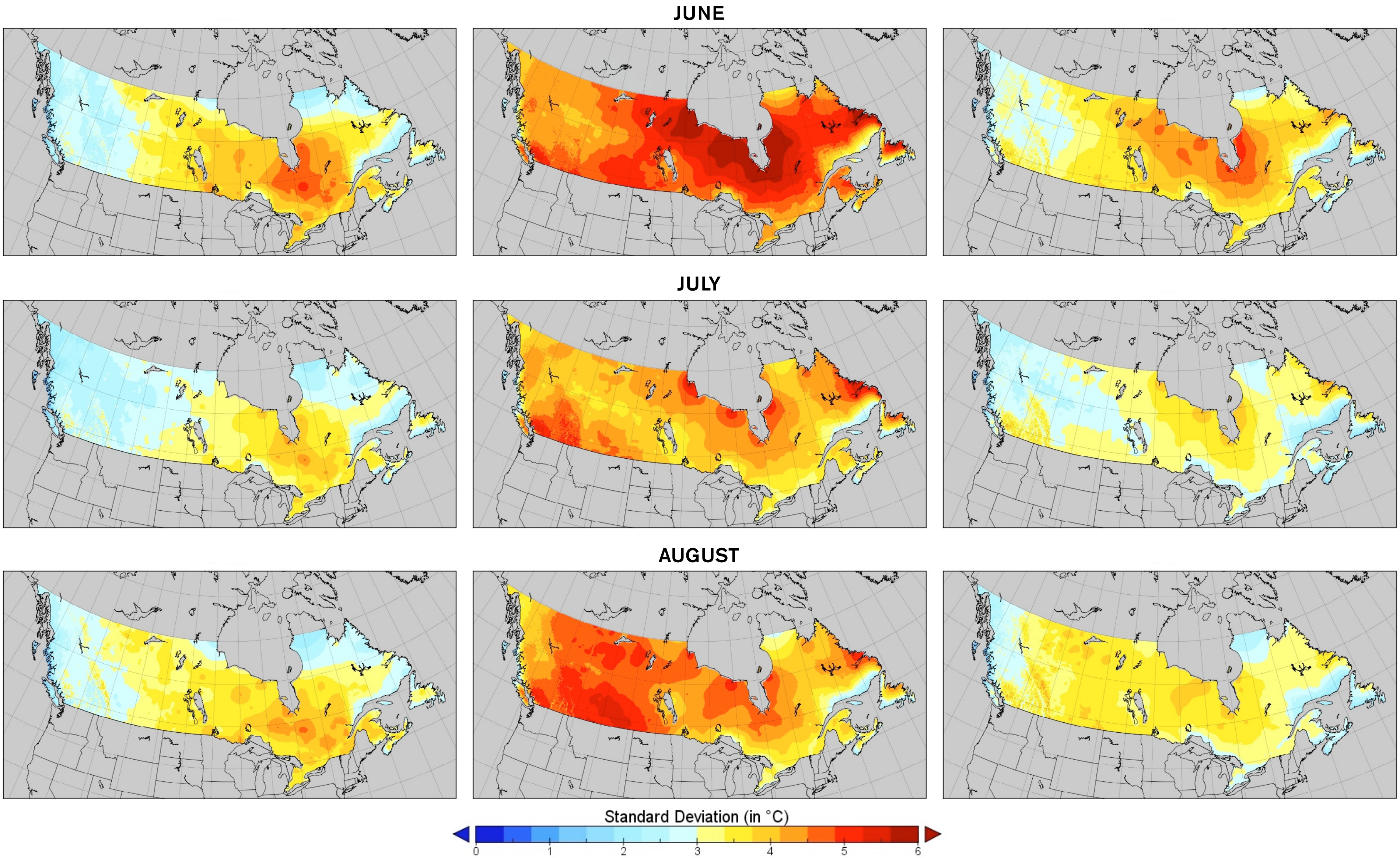


Figure C.2 Intra-monthly standard deviation* climatology using (1981–2010) Tmin/Tmax/Tavr Julian day climatology (left/centre/right panels) for June, July and August (from top to bottom panels, respectively). The data used is the same as for *Figure C.1*.



* The standard deviation STD_{ij} of the current month (i) of year (j) is defined by the equation: $STD_{ij} = \sqrt{\frac{\sum_{i=1}^{dmax}(X_{ij} - \bar{X}_i)^2}{dmax - 1}}$

Where X_{ij} corresponds to Tmin/Tmax of month (i) of year (j) and $(\bar{X}_i)$ is the climatological average of the Julian day for the 1981–2010 normal period for the month under consideration (i) of the daily minimum/maximum temperature. $dmax$ is the maximum number of days in month (i).

Appendix D. Climatology (1981–2010) of heat waves using several definitions (Section 4)

Figure D.1 Seasonal (summer: JJA) climatology of heat waves (in number of average sequences over 30 years) following various periods (3 to 6 consecutive days, left and right panels, respectively) with several Tmax thresholds (≥ 3 °C, 5 °C and 90th Tmax percentile, i.e.; Tmax90p, compared to 1981–2010 climatological reference values, panels from top to bottom, respectively). These heat wave indices were developed from the same data used in *Figure C.1* (Appendix C).

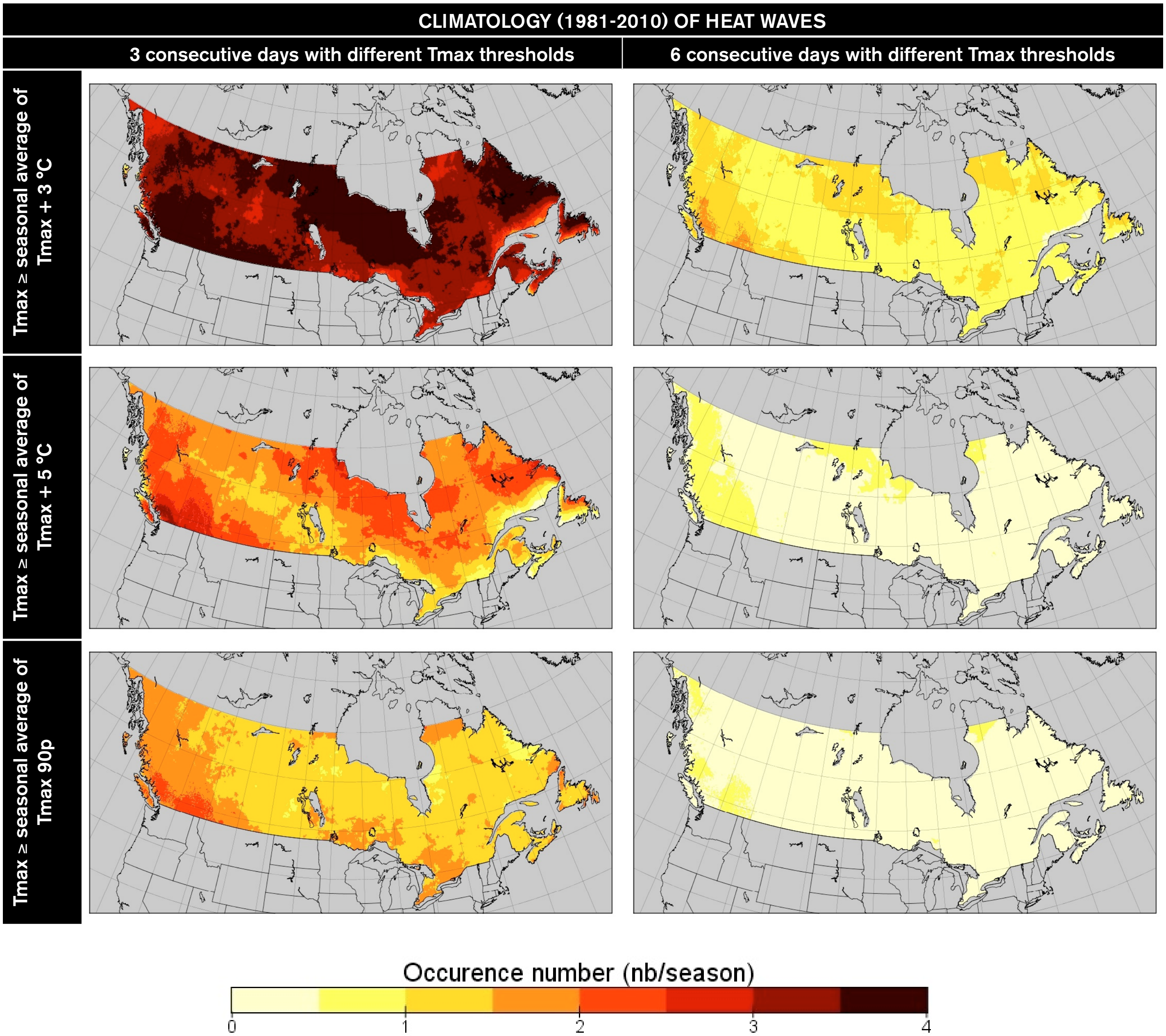
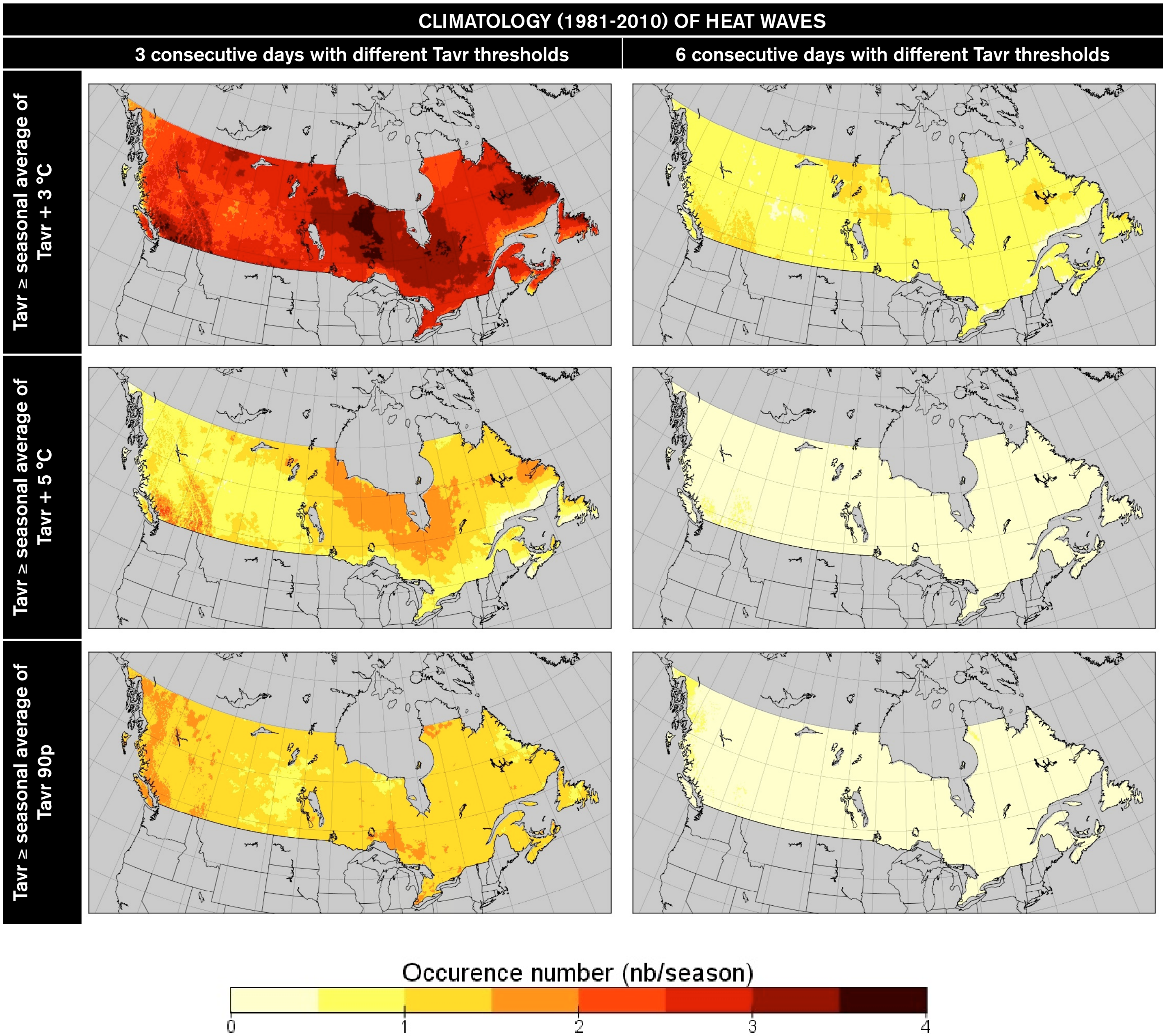


Figure D.2 **Seasonal (summer: JJA) climatology of heat waves (in number of average sequences over 30 years) following various periods (3 to 6 consecutive days, left and right panels, respectively) with several Tavr thresholds (≥ 3 °C, 5 °C and 90th Tavr percentile, i.e.; Tavr90p, compared to 1981–2010 climatological reference values, panels from top to bottom, respectively). These heat wave indices were developed from the same data used in *Figure C.1* (*Appendix C*).**



Appendix E. Thresholds of extreme heat warnings in Québec

TABLE E.1. Extreme heat warning thresholds in Québec, according to public health authorities and Québec health regions (RSS – Régions sociosanitaires du Québec).

RSS		WEIGHTING COEFFICIENTS (j1 – j2 – j3)	THRESHOLDS	
			T max (°C)	T min (°C)
Class 1				
RSS 01 RSS 02 RSS 03 RSS 08 RSS 09 RSS 10 RSS 11	Lower St. Lawrence Saguenay–Lac-Saint-Jean National Capital Abitibi-Témiscamingue North Shore Northern Québec Gaspé–Magdalen Islands	0.4 – 0.4 – 0.2	31	16
Class 2				
RSS 04 RSS 05 RSS 07 RSS 12 RSS 15	Mauricie and Québec Centre Eastern Townships Outaouais Chaudière-Appalaches Laurentians 1 (Mont-Tremblant Park, Mont-Laurier)	0.5 – 0.5	31	18
Class 3				
RSS 06/13 RSS 14 RSS 15 RSS 16	Montréal/Laval Lanaudière Laurentians 2 (Laurentians, Lachute – Saint-Jérôme) Montérégie	0.4 – 0.4 – 0.2	33	20

Appendix F. Current (1971–2000) and future (2041–2070 and 2071–2100) climatology and future (2050s and 2080s vs. 1980s) heat wave anomalies according to multivariate criteria (from RSS Class 3 presented in Table E.1, Appendix E)

Figure F.1. Averages and climatological anomalies (May to September) of the number of heat waves (average number of occurrences per year) based on at least 3 consecutive days of Tmin ≥ 20 °C, Tmax ≥ 33 °C and humidex ≥ 40 (jointly on the same day) for North America for a) the current period (1971–2000), b) future periods (2041–2070 top panel, and 2071–2100 bottom panel) and c) future anomalies (2041–2070 – 1971–2000 top panel, and 2071–2100 – 1971–2000 bottom panel). These values correspond to the average of 6 or 7 regional climate simulation models (details on these models are provided in *Table F.1*) for the current or future period (respectively) based on the data available from the CORDEX project (https://na-cordex.org/). For the future, the RCP8.5 scenario is used. The Tmin/Tmax thresholds used are based on *Table E.1* (RSS Class 3, *Appendix E*).

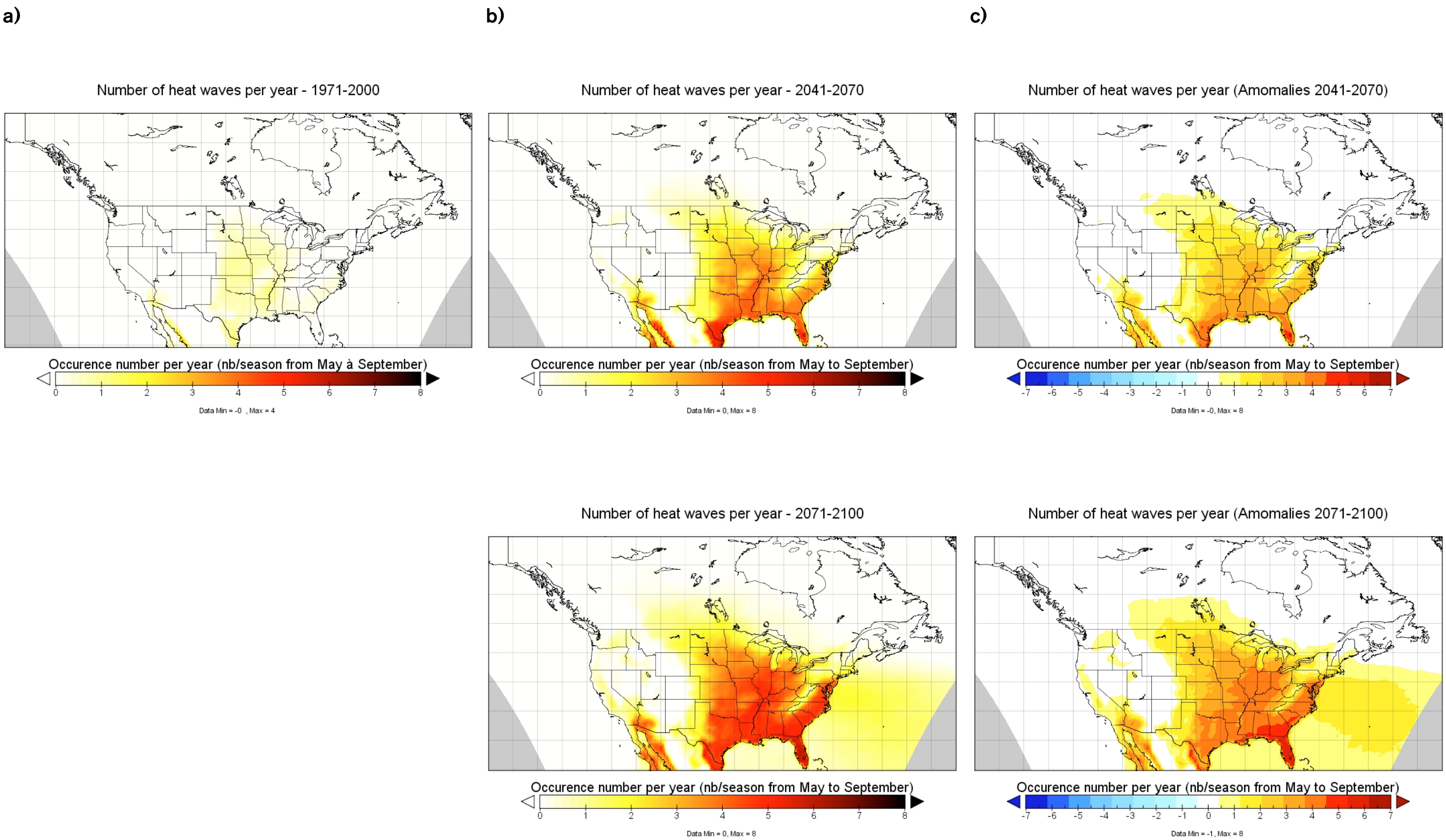


Figure F.2. Climatology of heat waves (period of May to September in Canada and the USA), using Tmin/Tmax thresholds and the same periods as those used in *Figure F.1* (i.e., not humidex due to unavailability), reconstructed from the ANUSPLIN database (Canada, see *Appendix C, Figure C.1*) and from the North American Land Data Assimilation System (NLDAS, USA). More details on NLDAS data are available at https://climatedataguide.ucar.edu/climate-data/nldas-north-american-land-data-assimilation-system-monthly-climatologies and in the study by Maurer *et al.* (2002).

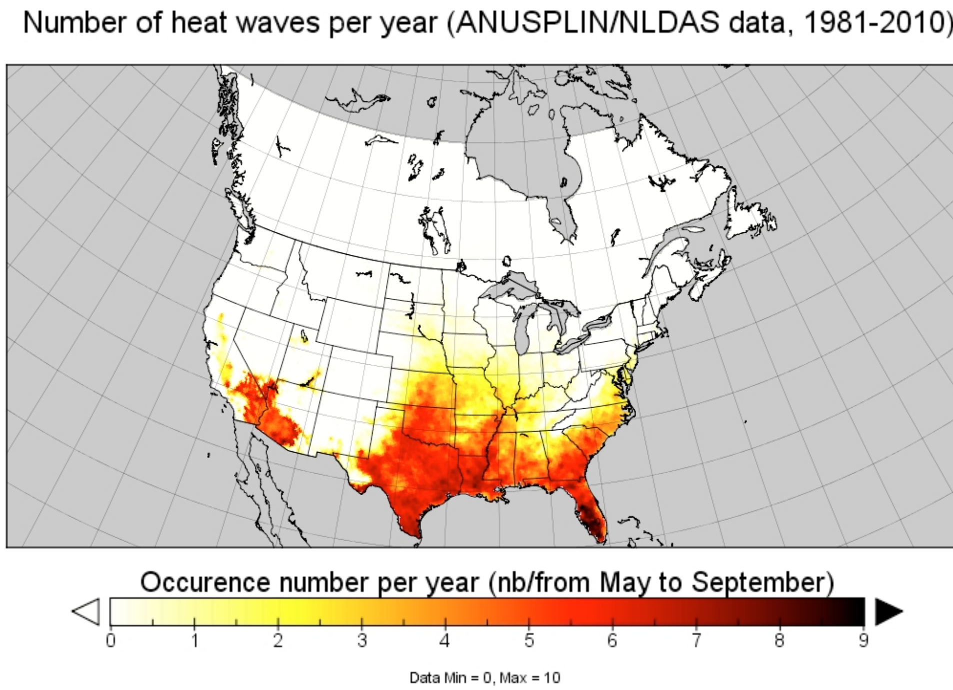


TABLE F.1. **Regional models driven by global models on the current and future available periods via the CORDEX project and used to develop the information presented in Figure F.1. The detailed description of the domain size, the models' main features, the type of projection and the analysis period are described in brief. References and documentation regarding these regional climate models are available on the North American CORDEX project website: https://na-cordex.org/simulation-matrix**

	UQAM-CRCM5	CCCMA-CANRCM4	DMI-HIRHAM5-V2	SMHI-RCA4-V1
Institution in charge of the model	Université du Québec à Montréal, Canada	Canadian Centre for Climate Modelling and Analysis, Victoria, Canada	Danish Meteorological Institute	Swedish Meteorological and Hydrological Institure (SMHI)
Acronym	**CRCM5-V1**	**CANRCM4**	**HIRHAM5-V2**	**RCA4-V1**
Driver / simulation period	CanESM2: 1971-2000	CanESM2: 1971-2000	ICHEC-EC-EARTH: 1971-2000	CanESM2: 1971-2000
	MPI-ESM-LR: 1971-2000	CanESM2_rcp45: 2041-2070	ICHEC-EC-EARTH_rcp45: 2041-2070	ICHEC-EC-EARTH: 1971-2000
	CanESM2_rcp45: 2041-2070			CanESM2_rcp45: 2041-2070
	MPI-ESM-LR_rcp45: 2041-2070			ICHEC-EC-EARTH_rcp45: 2041-2070
Projection and resolution	Rotated pole 0.44	Rotated pole 0.44	Rotated pole 0.44	Rotated pole 0.44
Convective scheme	Kain and Fritsch (1990) Kuo (1965)	Zhang and McFarlane (1995)	Tiedtke (1989)	Kain and Fritsch (1990, 1993)
Radiative scheme	Li and Barker (2005)	Li and Barker (2005), Barker *et al.* (2008) Pincus *et al.* (2003)	Fouquart and Bonnel (1980) Mlawer *et al.* (1997)	Savijarvi (1990) Sass *et al.* (1994)
Distribution of vertical turbulence	Benoit *et al.* (1989) Delage et Girard (1992) Delage (1997)	Abdella and McFarlane (1997); von Salzen *et al.* (2013)	Louis (1979)	Cuxart *et al.* (2000)
Microphysics scheme	Sundqvist *et al.* (1989)	von Salzen and McFarlane (2002), von Salzen *et al.* (2013)	Tiedtke (1989), Tompkins (2002)	Rasch and Kristjanson (1998)
Surface scheme	CLASS 3.5, Verseghy (2000)	CLASS 2.7	Schulz *et al.* (1998) Hagemann (2002)	Samuelsson *et al.* (2006)

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