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Heat Wave Hazards: An Overview of Heat Wave Impacts in Canada

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Abstract. Extreme heat events are natural hazards affecting Canada and many other regions of the world. This paper presents an overview of the issues involved in defining heat waves and harmful hot weather events, followed by a spatial and historical overview of heat waves across Canada, and an assessment of heat wave adaptation potential in selected cities. The Prairies, Southern Ontario, and areas in the St. Lawrence River Valley of both Ontario and Quebec demonstrate the highest temperatures and most frequent occurrences of heat waves, with minimal effects in the North, Pacific Coast, and Maritimes. Montreal frequently experiences extreme heat, and based on its low air conditioning rates and older, high-density housing, it demonstrates limited potential for adaptation to heat events. A scientific assessment was done to identify the effects of heat waves on various sectors of Canadian life including agriculture, livestock, fisheries, construction, transportation, utilities, the environment, and human health. Heat stress has been linked to excess human mortality and illness, violent behaviour, drought, forest fires, tornadoes, decreased agricultural and livestock productivity, construction and transportation difficulties, and reduced electrical power supply. Despite limited research on heat waves in Canada, this study demonstrates that the impacts of heat are profound and far-reaching.

Key words: heat wave, Canada, extreme heat, human health, livestock, agriculture, transportation, heat stress

1. Introduction

Limited work has been done on the effects of extreme heat events in Canada across various sectors. Despite documented increases in deaths associated with extreme heat events, especially in Southern Ontario and Quebec (Kalkstein and Smoyer, 1993; Smoyer *et al.*, 2000), heat waves are a relatively unfamiliar Canadian natural hazard. Although heat waves rarely cause the physical destruction that draws attention to extreme events such as hurricanes, floods, and tornadoes, the death toll accompanying heat waves is substantially higher. For example, the U.S. National Climatic Data Center (2001) reports that in the United States, the heat wave of 1988 resulted in an estimated 5,000–10,000 excess deaths, while 10,000 excess deaths have been attributed to the 1980 heat wave. (These numbers range widely because of a lack of uniform reporting of heat-related deaths and include deaths from all causes, rather than just directly from the heat). In contrast, the number of deaths resulting from each of the major floods, hurricanes, and blizzards in the U.S. between 1980 and 2000 ranged from 0–270, with an average of 44 deaths per event (National Climatic Data Center, 2001). A large number of deaths in Canada are suspected to be heat-related but are not labelled as such. This is due primarily to inconsistencies in cause of death reporting associated with assessing the effects of heat stress on human health (Chapman, 1995). Because mortality due to heat waves is largely preventable, knowledge of such events and their impacts is important for public health promotion. Less is known about the impacts of hot weather on other sectors within Canada, such as environment, infrastructure, and transportation. However, studies from regions more subject to weather-induced heat stress, including the United States and Australia, reveal useful information about how heat stress is likely to affect various sectors in Canada. These studies also provide valuable information about adaptation strategies, which may be essential if temperatures warm as expected under climate change scenarios.

The historical and spatial frequency of heat waves across Canada was investigated. Then, a scientific assessment of government documents, newspaper articles, and peer-reviewed journals was used to determine what information is available on the effects of heat waves on human health and behaviour, agriculture and livestock, construction, transportation, utilities, and the environment, with a focus on Canada. In addition, the consequences of climate change on the frequency and duration of heat waves, and on mitigation and adaptation were investigated, including an assessment of adaptation potential in selected Canadian cities. Finally, knowledge gaps were identified.

2. Defining Heat Waves and Harmful Hot Weather Events

One of the difficulties in commencing research on hot weather impacts lies in defining heat waves and heat stress events. Defining these conditions involves several components: heat wave characteristics; absolute versus relative measures; and heat stress indexes for assessing heat impacts on living organisms. The Merriam-Webster dictionary (2001) defines heat waves in relative terms, as "a period of unusually hot weather". Environment Canada (1996) provides a more scientific and absolute definition of a heat wave as a period of more than three consecutive days of maximum temperature at or above 32 °C. However, adverse heat impacts on humans have been noted at less extreme temperatures and shorter duration (Kalkstein and Davis, 1989; Smoyer *et al.*, 2000). Research on heat and human mortality also has demonstrated regional differences in health effects from extreme heat (Kalkstein and Davis, 1989; Kalkstein and Smoyer, 1993; Kalkstein and Greene, 1997).

Several characteristics of heat waves affect their impact: their frequency (both in a given summer and the number of events over a longer time period); their duration; and their intensity. Additionally, daily minimum temperatures play a role in extreme heat events. Nightly minimum temperatures offer relief from high daily maximum temperatures. When night temperatures remain high, humans, organisms, crops, and livestock do not get relief from the heat. Duration and intensity are reflected in various heat wave definitions, such as Environment Canada's absolute definition given above. Higher frequency of hot and humid conditions does not necessarily result in more severe heat wave impacts. In areas where hot and humid summer conditions are common, physiological, behavioural, and infrastructure adaptation is more likely and thus the harmful effects of heat stress may be reduced. Another component affecting heat wave impacts is the onset of the first heat wave within the summer season. Heat waves occurring earlier in the summer season have been shown to have a greater impact on human mortality, before short-term acclimatisation to hot weather has occurred (Kalkstein, 1991; Kalkstein and Smoyer, 1993). The effects on humans are well understood but little research has been done on the effects of early heat wave onset on plant, animal, or fish populations.

Heat waves can be defined using absolute and relative approaches. An absolute definition of a heat wave would require a certain number of days that exceed some pre-determined temperature or heat stress index level. This approach implicitly assumes that all populations respond similarly to each successive level of heat stress. Relative approaches, however, take into account acclimatisation to weather and that responses to heat stress differ depending on regional climate normals. Thus, what might be anomalous hot weather in a cooler climate like Halifax might be within summer normals in a warmer area like Toronto.

2.1. HEAT-STRESS INDEXES

Heat stress – that is, conditions that have the potential to cause physical harm to living things – may occur at less adverse conditions than those meeting heat wave criteria such as Environment Canada's (as outlined above). Thus, research of hot weather impacts, particularly for human health, requires the definition of heat stress events, which may differ from heat waves in the meteorological sense. Many methods for defining heat stress exist: univariate, bivariate, and multivariate indexes; and, air mass typologies. Any heat stress index can be used as an absolute or relative measure of heat stress. Univariate heat stress measures typically designate subjective cut-off points above which health effects are expected to occur. Examples include maximum temperature levels (e.g., 30°, 35°, 40 °C, etc.) or the number of consecutive hours or days above some specified temperature. Bivariate indexes typically include temperature and humidity and multivariate indexes tend to incorporate some combination of wind speed and/or solar radiation that affects the body's ability to dissipate heat. Humidex (Masterton and Richardson, 1979), humiture (Winterling, 1979), and the discomfort, or temperature-humidity index (Thom, 1959) are examples of the many existing bivariate indexes.

Multivariate heat stress indexes provide a more detailed description than univariate or bivariate indexes. Examples of multivariate indexes include: apparent temperature, also known as the heat index (Steadman, 1984); wet bulb globe temperature (United States Departments of the Army, Navy, and Air Force, 1980); and the National Meteorological Service of Germany's "Klima-Michel" model, which uses a radiation model of the human body to assess heat stress (Jendritzky and Nübler, 1981). Some of the most comprehensive heat stress indexes include air mass-based approaches (Kalkstein, 1991, 1998; McGregor *et al.*, 1999) that use a combination of weather variables to identify air masses with similar meteorological conditions. Other potential considerations for heat stress indices include factors such as the onset of the event within the summer season; the duration of the event; concurrent air quality levels; micro-climatic variation; or high-risk populations.

The aim of heat stress indices is ultimately to be able to predict heat wave weather situations that may lead to adverse effects in various sectors, and to do so both simply and accurately. An index that includes relative humidity is important in determining heat stress in humans, and also may be preferable when looking at the effects of heat on livestock because animals, like humans, probably experience some degree of acclimatisation. While relative and multivariate approaches are desirous for studying human and livestock health, absolute, univariate approaches may be sufficient for studies in other sectors. For example, when looking at the effects of heat on tire blowouts or on infrastructure such as roads, power lines, and water supply systems, absolute criteria, such as maximum temperature and number of days above some pre-selected temperature, may be sufficient for prediction.

3. Historical Heat Wave Events

Since little is known about the extent or frequency of heat waves across Canada, a spatial and historical overview was performed using both absolute and relative approaches, based on a more comprehensive report submitted to Emergency Preparedness Canada (Bellisario *et al.*, 2001). Absolute criteria allow uniform comparison of heat events across geographical areas and time periods. Alternatively, the relative approach uses temperature percentiles to facilitate comparison of anomalous, extreme summer weather conditions for different regions. While a temperature of 30 °C in Vancouver or Charlottetown would be highly anomalous and could exact a great toll on human health (and quite possibly infrastructure as well), the same conditions in Winnipeg, where summer temperatures above 30 °C are more common, would be expected to have lesser health impacts. Upper percentiles, however, may not make sense as heat waves in some regions (e.g., the far North).

Periods of record ranging from 51–104 years were analysed from 1 June–31 August for 16 stations, representing major cities in all ten provinces and three territories. The absolute approach involved identification of the number of occurrences of two or more consecutive days with maximum temperatures $\geq$30 °C, including the mean number of events per year (Table II). The relative approach involved plotting the temperature corresponding to the 1st, 5th, 10th, 90th, 95th, and 99th percentiles for each station for the study period (Figure 1). To supplement this

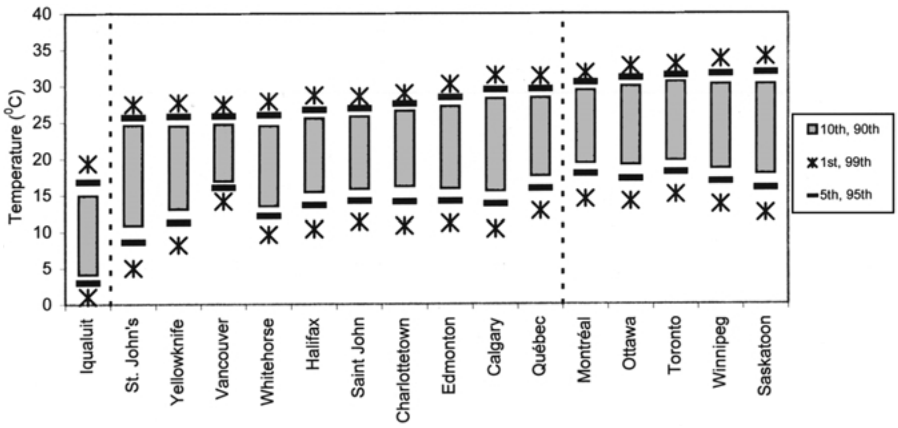

Figure 1. Summer maximum temperature percentiles for various Canadian cities 1961–1990. Cities to the right of each dashed line have summer maximum temperatures in the 95th percentile that are greater than 25 °C and 30 °C, respectively. All data were recorded at airports within or close to each city. Summer is defined here as 1 June–31 August. Data obtained from Bellisario *et al.*, 2000.

information, descriptions of major heat wave and heat stress events occurring in Canada were included (Table 1).

The results demonstrate that heat stress events have affected most areas of Canada to varying degrees. More events occur in Ontario and Quebec than elsewhere in Canada, yet heat waves have had harmful effects in the Atlantic Provinces as well as Yukon (Table 1). Using the absolute approach to identify the frequency of heat waves lasting 2, 3, 4, and 5 or more days for the same cities, it is evident that the Prairies, Southern Ontario, and the St. Lawrence River Valley region of Quebec experience the highest incidence of heat waves (Table II). Conversely, the North, Pacific Coast and Maritime regions experience minimal heat wave events, with no 2-day consecutive episodes of $\geq$ 30 °C in Iqualuit and $\leq$5 occurrences in Vancouver, Yellowknife, St. John's, and Halifax for the entire period of record. Toronto has the highest count of extreme heat events in Canada, averaging 4 episodes per year for the 62-year period of record. Not surprisingly, most heat wave research has focused on Toronto and Southern Ontario.

Examining mean temperature values as percentiles, it can be seen that the Prairies experience the highest maximum temperature range, followed by Southern Ontario and Quebec (Figure 1). Similar to the absolute approach, the relative approach demonstrates that even the 99th percentile of summer temperatures in the Pacific Coast, the North, and the Maritimes is below 30 °C. It is notable that Winnipeg and Saskatoon recorded the highest maximum temperatures (Figure 1) of the cities analysed, but experience $\geq$ 30 °C temperatures less frequently and of shorter duration than Toronto or Ottawa (Table II).

Table I. Historical heat wave and heat stress events in Canada

Date	Event
July, 1936	Heat wave in Ontario killed 458 people (Hofmann *et al.*, 1998).
August, 1953	The longest heat wave on record (August 25 to September 3) warmed lake Erie to a point where millions of fish were killed (Hofmann *et al.*, 1998)
August, 1995	Quebec registered temperatures up to 6oC above normal (Sundt, 1995) Tornadoes such as the one in Pine Lake, Alberta are expected to become more frequent with warmer, moister air conditions (David Suzuki Foundation, 2001)
Summer 1999	Third year in a row where extreme heat and drought wilted crops, endangered livestock and forced fire bans in Atlantic Canada (Environment Canada, 1999).
Summer 1999	Cities in Southern Ontario and Quebec experienced twice as many hot days (>30 °C) than the summer normal. Ottawa experienced 26 days >30 °C compared to a norm of 12 days per year (Environment Canada, 1999).
Summer 1999	Minimal precipitation and hot dry weather contributed to extreme fires in the Northwest Territories eventually burning 3 million hectares of boreal forest (Simpson, 1996).

4. Heat Wave Effects by Sector

4.1. HEALTH AND HUMAN BEHAVIOR

Heat stress events adversely affect both human health and human behaviour (Kalkstein and Smoyer, 1993; Anderson, 1989). Heat events can directly affect morbidity through heat cramps, heat exhaustion, and non-fatal heatstroke; and, mortality through heatstroke. Physiological stresses include dehydration, fatigue and a reduced ability to perspire or cool the body. Early symptoms can commonly be treated by moving to cooler, shaded environments and by increased consumption of fluids (United States Departments of the Army, the Navy and the Air force, 1980). Indirect heat effects include increased risk of death from cardiovascular disease, cerebrovascular accidents and vascular lesions, respiratory diseases, and increased susceptibility to infectious diseases (Kilbourne, 1989). Heatstroke is often under-reported as a cause of death (Kilbourne, 1989; Chapman, 1995). Heat stress exacerbates many underlying health conditions, and thus can lead to increased mortality from various causes rather than solely from heatstroke. Several studies have shown increases in excess mortality compared to baseline conditions during heat events (Kilbourne, 1989; Whitman *et al.*, 1996; Smoyer *et al.*, 2000).

Studies have shown that low-income and socially isolated persons, the elderly, and those with pre-existing health conditions, as well as residents lacking air conditioning and in high-density, older housing stock with limited surrounding

Table II. Number of heat waves that occurred in Canadian cities and their duration in days. Data obtained from Bellisario *et al.* (2000).

Location	Province	Number of Years on record (period of record)	Heat Wave Counts				# Events/ Years of record
			2 Days	3 Days	4 Days	5+ Days	
Vancouver	BC	63 (1937–1999)	2	0	0	0	0.03
Whitehorse	YT	56 (1943–1998)	6	0	0	1	0.13
Yellowknife	NT	56 (1943–1998)	3	2	0	0	0.09
Iqualuit	NU	51 (1946–1996)	0	0	0	0	0.00
Edmonton	AB	83 (1916–1998)	48	10	0	2	0.72
Calgary	AB	104 (1895–1998)	84	21	12	10	1.22
Saskatoon	SK	104 (1895–1998)	165	70	30	29	2.83
Winnipeg	MB	104 (1895–1998)	170	92	40	34	3.23
Ottawa	ON	60 (1939–1998)	103	48	27	29	3.45
Toronto	ON	61 (1938–1998)	105	78	33	33	4.02
Quebec	QC	100 (1895–1994)	84	36	18	5	1.43
Montreal	QC	53 (1942–1994)	61	29	20	17	2.40
Saint John	NB	104 (1895–1998)	6	2	0	0	0.62
Halifax	NS	54 (1945–1998)	4	1	0	0	0.09
Charlottetown	PE	98 (1895–1992)	17	3	0	3	0.23
St. John's	NF	104 (1895–1998)	4	0	0	0	0.04

vegetation, are most susceptible to the effects of extreme heat (Centers for Disease Control, 1981; Kilbourne *et al.*, 1982; Semenza *et al.*, 1996; Smoyer, 1998). Location also plays a significant role in population vulnerability. Heat-related deaths are often higher in urban areas compared with their surrounding areas due the urban heat island effect (Buechley *et al.*, 1972; Clarke, 1972; Smoyer, 1998). Increased temperatures have also been linked to increases in the rates of violent crimes including rape, murder, spousal abuse, riots, and other aggressive behaviour (Rotton, 1986; Anderson and Anderson, 1996).

Adaptation to hot and humid conditions can occur both from early-in-life exposures, and from short-term acclimatisation (Ellis *et al.*, 1975; Persinger, 1980), which can occur after the onset of the first bout of hot and humid weather of the summer season. Acclimatisation to a perpetually hot climate occurs during childhood and may be linked to activation of a greater percentage of sweat glands than would occur in an individual raised in a more moderate climate (Diamond, 1991). For individuals unacclimatised to hot weather, adaptation typically occurs within a few days of exposure to hot conditions, with an increase in the ability to sweat (Candas, 1987; Diamond, 1991).

Few studies have examined the effects of heat waves or heat stress on human health in Canada. The most comprehensive Canadian study to date examined climate/heat-related mortality relationships for 10 cities across Canada for the period 1958–1988 (Kalkstein and Smoyer, 1993). Both a threshold temperature (based on the temperature at which mortality dramatically increases for a given location) and an air mass-based approach were used. Of the ten cities analysed, only three demonstrated elevated mortality associated with hot weather. The air mass-based, synoptic climatological approach identified offensive air masses with excess mortality in Montreal, Toronto and Ottawa. The threshold temperature approach identified a statistically significant increase in mortality above 29 °C in Montreal and above 33 °C in Toronto (Kalkstein and Smoyer, 1993), both of which are cooler than threshold temperatures in many U.S. cities (Kalkstein and Davis, 1989). Neither method revealed a significant increase in mortality rates during heat wave events for St. John's, Halifax, Quebec, Winnipeg, Edmonton, Calgary, or Vancouver (Kalkstein and Smoyer, 1993). Thus despite the heat wave frequency and intensity demonstrated in Winnipeg (Table II, Figure 1), there is no evidence of excess mortality in that city.

More recent work on five cities in Southern Ontario revealed that mortality among the population ≥ 65 increased above baseline levels during episodes of hot and humid weather (as measured by a heat index >32 °C) in Toronto, London, and Hamilton. The Kitchener-Waterloo-Cambridge area experienced a slight increase, while no significant change was noted in Windsor, even though heat events of the highest intensity, longest duration, and greatest frequency occur in that region (Smoyer *et al.*, 2000).

Extreme heat events are often associated with increasing pollutant levels, which also affect human health. When nitrogen oxides, carbon monoxide, hydrocarbons, particulate matter, lead and industrial pollutants are combined and catalysed by sunlight, ground-level ozone and acidic aerosols result in smog formation and acidic deposition (Green, 1995). The rate of production of smog is dependent on the intensity of solar near-UV radiation and the concentration of pollutants present in the atmosphere (Dickerson *et al.*, 1997). High levels of ground-level ozone have been linked with increased emergency room visits and elevated cases of respiratory ailments in people with asthma and cardiovascular illnesses (Green, 1995; Burnett *et al.*, 1999; Kondro, 2000).

4.2. AGRICULTURE AND LIVESTOCK

Heat stress conditions often occur in conjunction with dry spells or drought conditions (Jiang and Huang, 2000; Huth *et al.*, 2000). As with human health and behaviour, heat stress on crops and livestock is relative to the tolerance ranges of each organism. Plants, such as Kentucky Bluegrass (widely used for home lawns) and Creeping Bentgrass (often used on golf greens), are adapted to growing in cool environments (Jiang and Huang, 2000; Xu and Huang, 2001). Results of both laboratory tests and field studies on these grasses have shown that plants subjected to heat stress incur damage to the photosynthetic and root systems, as well as exhibit stomatal closure and reduced CO_2 uptake. When combined with drought conditions, Kentucky Bluegrass and Creeping Bentgrass may suffer permanent damage to their photosynthetic systems (Heckathorn *et al.*, 1998; Jiang and Huang, 2000; Xu and Huang, 2001). In cereal crops, high temperatures during grain filling may decrease crop yields, kernel density and grain quality in maize (Wilhem *et al.*, 1999) and wheat (Ferris *et al.*, 1998).

For a wide variety of plant species, heat stress initially is more damaging than dry spells, but over a longer time frame, water deficits cause the most damage to plants (Kirschbaum, 1996; Jiang and Huang, 2000). Vegetation can adapt to environmental stress, such as by reducing the number of stomata on leaf surfaces to minimise evapo-transpiration losses and by extending root systems down into the subsurface (Jiang and Huang, 2000; Xu and Huang, 2001). Not all species adapt equally well. There is evidence that high temperatures may reduce the relative competitiveness of a variety of crop species (including corn, rice, soybean, millet, corn, and peanut) compared to weed species (Patterson, 1995). Weed species may recover faster from heat stress periods, thus out-competing crop species and reducing crop yields.

In general, plants exposed to temperatures greater than 40 °C experience wilting. If exposure is prolonged, death may result. Furthermore, soil is adversely affected by extreme heat through warming and drying. Root damage, which limits nutrient uptake, may occur in warm soils (Xu and Huang, 2001).

Extreme heat also adversely affects livestock reproduction, activity, milk production, dietary intake, and animal survival. For example, cattle experiencing heat stress will eat and ruminate less, and may die if their body temperature reaches 41.5 °C (Coventry and Phillips, 2000). Studies have found that fertility and conception rates in dairy cattle decrease markedly in the summer months when animals suffer from heat stress (Fuquay, 1981; Cavestany *et al.*, 1985; Thatcher, 1985). In swine, the optimum ambient temperature for breeding animals is 7–21 °C, with death possible at higher temperatures (Bactawar and Luymes, 2000). At temperatures above the comfort zone, sow feed intake decreases, which in turn leads to a decrease in weaning weights of pigs (Azain *et al.*, 1996; Johnston *et al.*, 1999). Poultry are highly susceptible to heat stress, particularly when in lairage, the buildings used to hold birds in modular crates between farm and slaughter (Roslin Institute, 1998). During extreme heat events, mechanical failures in cooling systems have resulted in the loss of thousands of birds in the southern United States (Faulk, 2000). In order to maintain livestock vigour during heat stress events, cooling and ventilation systems, shade provision, and diet alterations may be implemented (Fuquay, 1981; Cavestany *et al.*, 1985; Thatcher, 1985; Azain *et al.*, 1996; Bull *et al.*, 1997; Coventry and Phillips, 2000).

4.3. CONSTRUCTION, TRANSPORTATION, AND UTILITIES

Contrary to heat stress on organisms, which is often relative and may decrease with acclimatization and adaptation, heat stress on infrastructure is absolute. By understanding the thermal tolerances for ambient air temperature, or the degree of expansion/contraction for a given material, it is possible to design infrastructure that is adapted to given environmental conditions (Uzkan and Lenz, 1999). Problems can arise however, when the maximum threshold temperature for a particular material is exceeded.

Weather and climate are considered to be relatively minor factors affecting Canada's transportation sector but can have substantial associated costs. In general, the Canadian transportation sector is more susceptible to extreme winter events, while summer stresses are minimal (Andrey and Mills, 1999). Research on structures in hot climates, however, demonstrates that prolonged periods of summer heat may adversely affect construction as well as road, rail, and air transportation.

Extreme heat events affect road transportation in several ways, including engine and tire performance, air conditioning use, and road surface conditions. Internal combustion engines generate heat as a by-product of operation, and thus engine cooling is essential for efficient operation. Engine cooling ability is related to the size of the radiator, the fan and the ambient air temperature (Uzkan and Lenz, 1999). In this sense, it is possible to adapt engines to operate in warmer conditions by improving internal cooling systems. Tires are also susceptible to extreme heat events. Air expands as it warms and can increase tire pressure, thereby increasing the likelihood of a blowout (Grenci, 1995). Summer heat can be problematic in construction and for road and rail infrastructure. High ambient temperatures, particularly when coupled with low relative humidity, increased wind velocity, and high solar radiation, can lead to moisture loss in concrete during mixing and pouring, and thus result in cracking from thermal shrinkage (ACI Committee 305, 1991). Changes in temperature affect bridges as well, leading to expansion and contraction. Although organizations such as the American Association of State Highway and Transportation Officials (AASHTO) have guidelines for predicting thermal expansion in bridges, these specifications are less useful for predicting movement in curved bridges (Moorty and Roeder, 1992).

Heat can increase rutting of paved highways, resulting in higher maintenance costs and shorter life span. Furthermore, it may also cause flushing or "bleeding" of the asphalt surface, which can increase skidding, a safety concern (Andrey and Mills, 1999). Heat effects on rail infrastructure include track expansion or buckling, causing what are known as sun kinks, which can lead to train derailments (Benson, 1991; Grenci, 1995; Al Lyanders, Environment Officer, Canadian National, *Personal Communication*). However, winter threats, such as permafrost heaving, broken wheels, and frozen switches, pose far more serious threats to Canadian rail lines (Andrey and Mills, 1999; Al Lyanders, Environmental Officer, Canadian National, *Personal Communication*).

Air transport is also affected by temperature extremes. Current airplane designs are built to operate at temperatures ranging form −70 °C to 50 °C. Previously existing flight charts allowed aircraft flight up to temperatures of 48.9 °C. When temperatures reached 50 °C, air travel in Phoenix effectively stopped. Since then, flight charts have been adapted to allow aircraft take-off at temperatures up to 52.2 °C (Grenci, 1995). Aircraft use air density under the wings to provide the lift necessary for flight. Warmer air is less dense, therefore providing less lift to aircraft. If a plane takes 15 m to take off at 0 °C, it would require about 210 m to take off at 43.3 °C (Grenci, 1995). The increase in necessary runway distance is due both to the air density required for lift and the decrease in engine power of the aircraft as temperature increases. Maximum fuel efficiency in aircraft engines is obtained at temperatures below −50 °C (McKinley and Bent, 1972: Andrey and Mills, 1999), and thus warmer temperatures require more fuel.

High ambient temperatures also affect power infrastructure. Transducers in power generation operate by dissipating excess heat to the environment. Warmer air temperatures reduce the transducer's ability to dissipate heat to the environment, thereby reducing the efficiency of transmission lines (Hofmann *et al.*, 1998). Likewise, metal power lines expand under extreme heat conditions resulting in sagging lines. Power demands tend to increase during heat stress events as air conditioning use increases. In some instances, energy demand during heat events has exceeded supply, forcing cities such as New York to implement rolling blackouts in order to reduce energy demands (Explorerzone.com News, 1999). Thus heat events are particularly problematic because power demand increases at a time when transmission efficiency is reduced.

Water use is also affected by temperature, with demand typically increasing in summer. Studies of U.S. cities demonstrated that water use first increases above 21 °C, with substantial increases in demand above approximately 30 °C (Maidment and Miaou, 1986). In addition, a study of New York City showed that precipitation was highly important in summer for reducing water demand, while in winter precipitation had little effect on daily water use (Protopapas *et al.*, 2000). Under hot and dry conditions, municipal water demand is at its highest, at a time when water availability may be limited.

4.4. ENVIRONMENTAL EFFECTS

Ecosystems face many stresses either directly or indirectly associated with extreme heat events. As discussed in Section 4.2, direct effects include heat stress in plants and animals, soil moisture loss, and altered animal reproductive patterns. Indirect effects of extreme heat include drought, severe storms and wild fires (Huang *et al.*, 1998; Parmesan *et al.*, 2000; Jiang and Huang, 2000; Huth *et al.*, 2000). Prolonged heat stress may lead to lowered water table levels, poleward shifts in ecosystem distributions, constrained animal ranges, and altered gender distributions and physiological characteristics (IPCC, 2001). Consequently, species living at the edge of their tolerance zones are most susceptible to extreme heat events and long-term climate warming. It is important to note that effects at one trophic level can affect all subsequent levels (Parmesan *et al.*, 2000).

Limited information is available about the effects of heat stress on ecosystems. However, more is known about the effects of heat on fresh water ecosystems and fisheries. Sustained above-normal temperatures have been linked to the warming of water bodies, which in turn, restricts lake-overturning processes and can lead to anaerobic conditions at the lake floor. As water temperatures increase, dissolved oxygen available for fish respiration decreases. High temperatures can adversely affect fish through both acute and chronic stress. For example, in 1953, a prolonged heat wave caused Lake Erie to warm, which triggered extreme nutrient pollution. Coupled with already high pollution levels, the event resulted in a massive fish kill from lack of oxygen (Hofmann *et al.*, 1998). In 1998, a combination of heat and physiological stress incurred during catch and release led to a major bass die-off in a stocked reservoir in Southeast Texas (Texas Parks and Wildlife, 1998). Chronic effects of warmer temperatures extend throughout the fish lifecycle, from egg laying and hatching to maturity. Chronic heat stress can limit growth and adversely affect reproduction (Shuter, 1990). In sports fisheries, increased water temperatures have been associated with decreased activity and movement to deeper, cooler waters, which reduce fish catches. Some favoured species, such as bass, are particularly sensitive to heat (Texas Parks and Wildlife, 1998; Wattendorf, 1999).

As with the natural environment, heat stress also takes a toll on the built environment. In the case of the built environment, however, human modification often exacerbates hot weather conditions, as in the form of the urban heat island. The urban heat island (UHI) is a phenomena whereby urban areas experience warmer temperatures than neighbouring non-urban areas. It has been largely agreed that urban environments alter the radiative, thermal, moisture and aerodynamic characteristics of the surface (Oke, 1982; Morris *et al.*, 2001). Pavement and construction materials, particularly those that are dark coloured, tend to have a higher radiative absorption factor than soil, meaning that urban areas have more energy available for re-emission at night than do neighbouring rural areas. Although in winter, the UHI can result in reduced heating costs, it has negative consequences in summer. These include an increase in air conditioning use, and reduced nighttime cooling and heat stress relief during heat wave events (Landsberg, 1981).

Canadian research shows that downtown Toronto experiences significantly more heat wave events than Pearson's International Airport. Likewise, downtown Edmonton, Ottawa, and Montreal all experience more heat waves than their less developed peripheries (Bellisario *et al.*, 2001). Urban heat island effects can exacerbate risk for the most vulnerable populations. Research from the United States demonstrates that the inner city is not only hotter and less likely to cool in the evening than suburban and rural areas, but that residents in this area are more likely to live in poverty, and to inhabit older and high-density housing (Buechley *et al.*, 1972; Jones *et al.*, 1982; Semenza *et al.*, 1996; Smoyer, 1998).

5. Heat Waves and Climate Change

There is increasing evidence of climate change and projected increases in global mean surface temperatures ranging between 1.4–5.8 °C from 1990 to 2100 (IPCC, 2001). For North America, a 1–2 °C increase is expected by 2020 and 5–10 °C by 2090. Even greater increases have been projected for the Arctic, with a 3–4 °C increase by 2020 and >15 °C by 2090 in some Northern regions (Hengeveld, 2000). Thus the frequency, duration, and intensity of heat waves in Canada are likely to increase. The Canadian regions with the highest population densities and the most productive agricultural zones are expected to suffer the greatest increased risk of adverse heat wave effects. Mitigation and adaptation to hotter temperatures and associated environmental conditions will become increasingly important over the next few decades. Mitigation in the form of more efficient energy use would help to curb greenhouse gas emissions, which are contributors to climate change. Adaptation of infrastructure, lifestyle choices, and emergency response systems will be essential to maintaining a healthy society.

6. Mitigation and Adaptation

Mitigation of heat waves may be possible by reducing urban heat island effects and reducing greenhouse gas emissions to slow climate change. In terms of adaptation to heat waves and heat stress, adaptive strategies have been implemented in all sectors, although most attention here is given to the health sector. The following sections focus on: environmental modification, including urban design, housing type, and air conditioning; behavioural modification through weather watch warning systems and public education; and finally, a synopsis of adaptation in other sectors.

6.1. ENVIRONMENTAL MODIFICATION

Heat stress conditions are predictable, and heat stress mortality is preventable. Populations in cities exposed to consistently high temperatures can take measures to reduce heat impacts in the form of modifications to both architecture and behaviour. Environmental modifications provide ongoing and "passive" (i.e., not requiring immediate action from at-risk individuals during heat events) heat stress risk reduction. These solutions require initial recognition that the area is subject to heat waves coupled with a willingness to allocate funds for environmental modification. In political climates where key decision-makers are on limited elected terms, it may be difficult to justify allocating funds in the absence of a health-threatening heat wave. Once the heat wave is occurring, it is usually too late to implement these life-saving environmental changes.

Urban design, a type of environmental modification, is a form of both heat mitigation and adaptation to heat wave conditions. Increasing green spaces, implementing innovative solutions such as rooftop and vertical gardens, and using light-coloured building and road surfacing materials can help to reduce temperatures and offset heat wave impacts. These solutions are particularly useful at night, to maximise the potential for radiative cooling. For example, rooftop and wall gardens regulate the urban heat island effect. These gardens can potentially reduce the urban heat island effect by 3–4 °C on a hot day, and can decrease air conditioning demand by 50–75% through direct shading and evaporative cooling (Environment Canada, 1999). Environment Canada (*no date*) has explored many options for adaptation through modification of urban areas, which are available on their webpage. The benefits of heat reduction through urban design extend to infrastructure and utility use, as well as human health.

6.1.1. *Housing Type and Air Conditioning*

Previous U.S. studies have identified air conditioning (with central air being more effective than window units), single family-detached dwellings, and modern housing (built within the previous 1–5 years) as effective strategies for reducing heat stress (Buechley *et al.*, 1972; Centers for Disease Control, 1981; Kilbourne *et al.*, 1982; Semenza *et al.*, 1996; Smoyer, 1998). Thus it is expected that residence in low-density, modern housing, and the use of air conditioning during extreme heat events could minimise mortality rates in Canada as well.

To investigate the adaptive potential to heat waves associated with housing type and air conditioning availability in Canada, dwelling characteristics for nine Canadian cities were analysed from the Household Income Facilities and Equipment (HIFE) survey (Statistics Canada, 1980–1995). Strong regional disparities are noted for air conditioning, with the highest rates occurring in Toronto, Winnipeg, Ottawa, and Montreal (Figure 2), the four cities whose 95th percentile exceeded 30 °C (Figure 1). Dwelling type (Figure 3) does not appear to differ between the warmer and cooler cities, although the four hottest cities analysed here generally had a greater percentage of older housing (Figure 4). It is notable that among the four hottest cities for which these data are available, Winnipeg and Toronto had the highest frequency of air-conditioned dwellings. Ottawa and especially Montreal had lower levels of air conditioning despite the high frequency of heat wave conditions in the two areas (Figure 2). In terms of heat-retaining, high-density housing units (duplex, row, and apartment dwellings), Montreal had the highest levels, followed by Toronto. Montreal also exhibited the largest percentage of dwellings built before 1941. Winnipeg had the largest percentage of single-family dwellings among the cities analysed, although it also had a relatively large proportion of housing built before 1941.

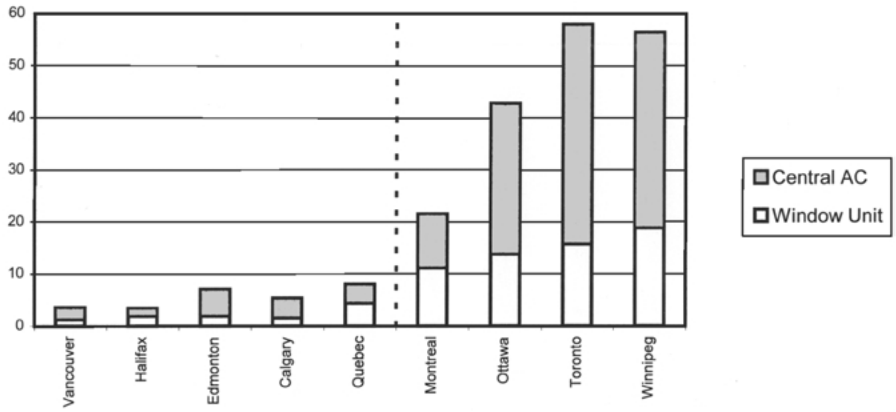

Figure 2. Percentage of households with air conditioning units (central and window) averaged for 1990–1995. Cities to the right of the dashed vertical line have summer maximum temperatures in the 95th percentile that are greater than 30 °C. Note that the cities that exceed this cutoff have the highest percentage of air conditioners. Data obtained from Statistics Canada, Household Income, Facilities and Equipment (HIFE) survey.

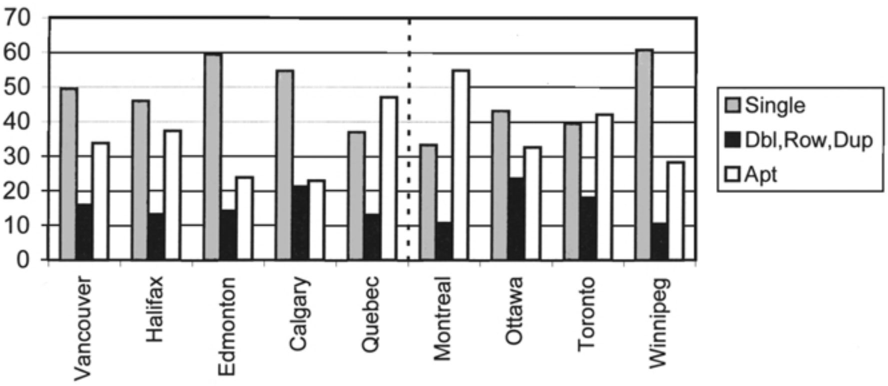

Figure 3. Percentage of dwelling type for various Canadian cities averaged for 1990–1995. *Single* = single detached dwelling; *Dbl*, *Row*, *Dup* = double, row, or duplex housing; *Apt* = apartment dwelling. Cities to the right of the dashed vertical line have summer maximum temperatures in the 95th percentile that are greater than 30 °C. Data obtained from Statistics Canada, Household Income, Facilities and Equipment (HIFE) survey.

Air conditioning currently is the most widely used strategy in the urban residential sector to mitigate the harmful effects of hot weather and to adapt to potential increases in heat events. In this regard, Montreal appears to be at the greatest disadvantage. Compared to Winnipeg, Toronto, or Ottawa, Montreal has lower air conditioning rates, more high-density housing and older housing units that may affect heat load and the ability to install air conditioning units. Winnipeg and Toronto, in terms of air conditioned dwellings, are better prepared for heat waves although

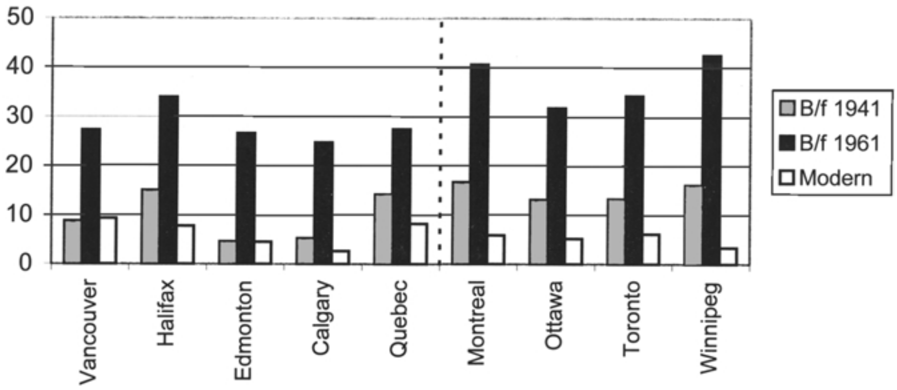

Figure 4. Percentage of dwellings built before 1941, before 1961, and modern dwellings (built within 5 years of the survey date). Values represent average dwelling age for 1990–1995. Cities to the right of the dashed vertical line have summer maximum temperatures in the 95th percentile that are greater than 30 °C. Data obtained from Statistics Canada, Household Income, Facilities and Equipment (HIFE) survey.

the high-density housing in Toronto and relatively older housing in Winnipeg may contribute to elevated health risks among populations lacking air conditioning.

6.1.2. *Hot Weather/Health Watch Warning Systems and Education*

Although the public health benefits may not be as significant as from environmental modification, behavioural modification during heat events is a more realistic response to an immediate problem. Education and awareness are key components of behavioural modification, and may include suggestions such as reducing activity, increasing fluid consumption, and checking on elderly relatives and neighbours during heat events. Like passive health interventions, this “active” risk reduction strategy requires planning well in advance of the summer season, but the costs are likely to be lower and the implementation less complicated than environmental modification. Effective communication of the onset of a dangerous weather event is a crucial component of weather watch/warning systems and emergency preparedness plans. An increasing number of North American cities are implementing weather watch/warning systems as a way of reducing the harmful effects of heat stress.

Weather watches, warnings, and advisories are frequently used to convey forecasts of severe weather to the public. In Canada, this information is used for events such as heat waves as well as cold snaps, storms, and high winds. With the exception of Toronto, however, no Canadian cities have formal heat wave warning systems in place, although plans have been discussed for other cities. A watch alerts the public that conditions are favourable for the development of severe weather. A warning conveys that severe weather is occurring or highly probable. An advisory indicates that either (1) actual or expected weather conditions may disrupt normal activities, but do not pose a serious threat to human safety, or (2) severe weather conditions may arise, but insufficient information is available to justify a warning (Environment Canada, 2000). The combined effort of city managers, public health department workers, and emergency medical officers is needed to develop a systematic plan that will provide assistance to the most vulnerable populations.

Given that Toronto has among Canada's highest frequency and longest duration of heat waves, it is not surprising that it is the first city in Canada to implement a weather watch/warning system for heat wave events. Similar plans are in place in Philadelphia, St. Louis, and Chicago in the United States; and in Rome, Italy, with new systems being continually developed and implemented (Kalkstein, 2000).

6.2. ADAPTATION IN OTHER SECTORS

Plant and animal scientists, farmers, fisheries managers, and engineers have devised a variety of strategies for reducing the harmful effects of heat stress on their corresponding sectors, which may be useful in the case of adaptation to increased incidence of warm conditions associated with climate change. Irrigation and changing crop types are means of mitigating heat wave effects on agriculture. Plants capture and incorporate CO_2 in two ways. C_4 plants do so at night when air temperature is lower, while C_3 plants must capture and incorporate CO_2 during sunlight hours, leaving them more vulnerable to water loss. For this reason, it is expected that C_4 plants are better able to deal with extreme heat events. However, C_4 plants are less efficient at capturing and using CO_2. Thus increased CO_2 levels may enable C_3 plants to out-compete C_4 plants, potentially offsetting the adaptive potential of C_4 plants. The future benefits of C_4 verse C_3 plants requires further research (Gillis, 1993).

In addition to developing heat- and drought-resistant crops, technological developments may help with adaptation to high temperatures. For example, kaolin-based hydrophobic particle films, currently under study and in limited use for suppression of pests and diseases, have been shown to reduce heat stress without compromising photosynthesis (Glenn *et al.*, 1999).

Many adaptation measures are already in use in the livestock industry. For example, tropically adapted cattle and acclimatised cattle, with shorter coats, have been bred in warm climates. Lean body condition and resting time are important, as are shaded but well ventilated yards and sprinklers to assist in cooling (Coventry and Phillips, 2000). Similarly, snout and drip coolers and conductive cool pads have been effective in reducing heat stress in swine (Bull *et al.*, 1997), while fans and ventilation tunnels have been useful for poultry (Roslin Institute, 1998). Dietary modification (Johnston *et al.*, 1999) and milk replacers (Azain *et al.*, 1996) have been used to offset reductions in feeding and milk production among swine.

In the transportation sector, the negative effects of warmer summer temperatures and associated heat stress pose far less of a concern than current winter threats. The benefits of warmer winter temperatures that would accompany climate change in most parts of Canada are expected to outweigh the slight increase in heat stress events (Andrey and Mills, 1999). For example, a warming would decrease winter hazards and associated costs such plane icing, and thus reduce stresses on air travel. Warmer temperatures may affect the maximum payload an aircraft can carry, although systems operate within current variation that is greater than that expected under climate change (Andrey and Mills, 1999). Therefore, climate warming, which under the most recent projections would remain within current engine and flight operating parameters, is expected to decrease winter stresses on air transportation while remaining within summer heat tolerances.

Nevertheless, transportation infrastructure must be designed to compensate for temperature extremes. This has already been seen in the case of aircraft and locomotive diesel engine designs (Grenci, 1995; Uzkan and Lenz, 1999). Railway ties have been built with smaller gaps between ties, and bridge design includes joints to allow for expansion and contraction (Benson, 1991). For roads and highways, higher temperatures will result in more rutting and bleeding in the road surface. High temperature-withstanding asphalt cements are available but are more expensive than those currently in use (Andrey and Mills, 1999). Thus a significant cost is likely to accompany adaptation to increased heat stress in the construction and transportation sectors. Older infrastructure may require reconstruction, but there is potential to incorporate new designs into upgrades and new construction projects.

Perhaps the most important mitigation and adaptation strategy, regardless of the sector, is that of public education and awareness. If the range of cross-sectoral heat stress impacts, in addition to preventative measures, are better known, multiple sectors can prepare for and adapt to extreme heat events.

7. Knowledge Gaps and Future Studies

Heat wave impacts are a function of a complex interaction of variables and affect many sectors that have not been well studied. Few studies in Canada have addressed heat waves in terms of historical and regional frequency or sectoral impacts. Most of the information in the scientific literature, both in peer-reviewed journals and government/NGO reports, about the impacts of heat waves per se comes from human health studies in countries where heat waves are frequent. Outside of the health sector, the scientific literature tends to focus on observed, controlled experimental, or simulated responses of organisms, infrastructure, or materials to high temperatures, rather than providing overviews of the impacts of specific heat waves. Thus much of the information about the effects of heat waves on these sectors is anecdotal and found in the popular media, rather than in the scientific literature. The range of available information on the responses of various sectors to heat waves and heat stress is nevertheless useful when gauging the types of impacts that might occur in Canada with warmer temperatures stemming from climate change, as well as potential adaptive strategies.

Due in part to the perception that Canada has a cold climate, heat waves have not been viewed as a serious threat in Canada. Research is needed to document the occurrence of heat waves and to expand the understanding of their impacts in diverse sectors and regions in Canada and internationally. More studies may emerge as heat waves become more recognised as a threat to Canadian society, particularly as concern grows about increased warming associated with a changing climate. Some key areas of research for Canada include threats to human health, electrical and water supply, drought frequency, storm severity, and the relationship between heat events, wild fires, and potential ecosystem shifts. Once heat events are better understood, more can be done to develop and implement mitigation and adaptation strategies.

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