

ORIGINAL ARTICLE

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Heat-stress-related mortality in five cities in Southern Ontario: 1980–1996

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Abstract The Toronto–Windsor corridor of Southern Ontario, Canada, experiences hot and humid weather conditions in summer, thus exposing the population to heat stress and a greater risk of mortality. In the event of a climate change, heat-stress conditions may become more frequent and severe in Southern Ontario. To assess the impact of summer weather on health, we analyzed heat-related mortality in the elderly (older than 64 years) in the metropolitan areas of Windsor, London, Kitchener-Waterloo-Cambridge, Hamilton, and Toronto for a 17-year period. Demographic, socioeconomic, and housing factors were also evaluated to assess their effect on the potential of the population to adapt and their vulnerability to heat stress. Heat-stress days were defined as those with an apparent temperature (heat index) above 32°C. Mortality among the elderly was significantly higher on heat-stress days than on non-heat-stress days in all cities except Windsor. The strongest relationships occurred in Toronto and London, followed by Hamilton. Cities with the greatest heat-related mortality have relatively high levels of urbanization and high costs of living. Even without the warming induced by a climate change, (1) vulnerability is likely to increase as the population ages, and (2) ongoing urban development and sprawl are expected to intensify heat-stress conditions in Southern Ontario. Actions should be taken to reduce vulnerability to heat stress conditions, and to develop a comprehensive hot weather watch/warning system for the region.

Keywords Heat-related mortality · Apparent temperature · Heat stress · Southern Ontario · Canada

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Introduction

Heat waves are responsible for a large number of deaths in North America. For example, in the United States, the heat wave of 1980 resulted in approximately 10 000 excess deaths, and the heat wave of 1988 resulted in an estimated 5000–10 000 deaths. In comparison, the number of deaths resulting from each of the major floods, hurricanes, and blizzards in the United States between 1980 and 1999 ranged from zero to 270, with an average of 41 deaths per event (National Climatic Data Center 1999). Clearly, the health risks that heat waves pose to the public warrant major concern.

Past research has observed heat-related mortality in Toronto and Montreal for the period 1958–1988, although this is of lesser magnitude than in many United States cities (Kalkstein and Smoyer 1993a,b). The results of these previous studies indicate that a climate change stemming from increasing greenhouse gas concentrations would elevate the risk of heat-related mortality for the population of Toronto, Montreal, and the surrounding areas, because of increased exposure to heat stress through more frequent and severe heat waves in these regions.

This study focuses on heat-stress/mortality responses in five cities in the Toronto–Windsor corridor of Southern Ontario, an area that experiences hot and humid weather conditions in summer. With regard to human health, vulnerability and adaptation to climate change in the Toronto–Windsor corridor are likely to be influenced by a combination of demographic composition, urban morphology, and socioeconomic conditions. By comparing heat-stress/mortality relationships within areas experiencing similar climatic conditions, this study begins to elucidate factors affecting vulnerability and adaptation to climate variability as expressed through heat-stress episodes.

The primary objectives of this research are (1) to identify the relationship between conditions expected to lead to heat stress and mortality for the largest cities in the Toronto–Windsor corridor, and (2) to identify potential demographic and socioeconomic risk factors in heat-stress mortality that may impede adaptation in the event of climate change.

Materials and methods

The research spans 1 June—31 August for each year between 1980 and 1996. The study includes the five largest cities (or amalgamations of adjacent cities) of the Toronto–Windsor corridor in Southern Ontario: Windsor, Kitchener-Waterloo-Cambridge (KWC), London, Hamilton, and the newly amalgamated city of Toronto, referred to as Metropolitan Toronto (Fig. 1). Metropolitan Toronto is the largest of the cities studied, with over 2×10^6 people, while Windsor is the smallest at just under 200 000 people as of 1991. The other three cities had 1991 populations ranging from 303 165 in London to 332 235 in KWC. Persons over 64 years of age comprised between 10.2% of the total population in KWC and 14.4% of the population in Hamilton (Table 1). Because the elderly population, represented here by persons over 64 years old, is more susceptible to weather-related mortality than younger populations, the results presented in this paper are for the elderly only.

An apparent temperature (T_{app}) approach, also known as the heat index, was adopted to identify heat-stress days. This measure takes into account human physiology and is based on the synergistic effects of high temperature and humidity and their ability to stress the body's thermal regulatory systems (Steadman 1984).

Table 1 Demographic characteristics of cities in the Toronto-Windsor corridor, 1991. *Elderly population* over 64 years old; *KWC* Kitchener/Waterloo/Cambridge

City	Total population	Elderly population (% of total)
Windsor	191435	27355 (14.3)
London	303165	35900 (11.8)
KWC	332235	33865 (10.2)
Hamilton	318499	46020 (14.4)
Metropolitan Toronto	2275771	291095 (12.8)

In previous research in St. Louis, Missouri, we have used a heat index of 40.6°C (105°F) as an indicator of heat-stress days (Smoyer 1998a), but the heat index in the Toronto–Windsor corridor rarely exceeds this value. Populations tend to respond to weather in a relative, rather than an absolute fashion (Kalkstein and Davis 1989), and thus we expect that heat-stress will occur under less severe conditions in this area. Therefore, we have evaluated the increase in mortality when the maximum heat index exceeds 32°C. This value (approximately 90°F) corresponds with the potential impacts on health of sunstroke, heat cramps, and heat exhaustion (Steadman 1979), and has been adopted by the United States National Weather Service for conveying heat-stress warnings.

We calculated apparent temperature (the heat index) as follows. First, we identified the maximum air (dry bulb) temperature for each day and selected the dew point temperature that occurred at the same hour as the maximum air temperature (which was not necessarily the maximum dew point temperature). The maximum daily air temperature and the corresponding dew point temperature were obtained from Environment Canada data. For 1 June–31 August for the 17-year period between 1980 and 1996, we used 24-h weather data from the Toronto Pearson, Windsor, and London airport stations; daytime data for Hamilton and Waterloo Wellington Airport were used since 24-h data were not available.

We calculated the apparent temperature from the following equation, which we derived from Steadman's table of air temperature, dew point temperature, and apparent temperature, assuming no or light winds (Steadman 1979):

$$T_{app}=-2.719+0.994T_{air}+0.016(T_{dewpt})^2 \quad (1)$$

where T_{air}=air temperature (°C) and T_{dewpt}=dew point temperature (°C). Days with T_{app} above 32°C are considered heat-stress days for each of the weather stations used in the analysis.

The term "heat-stress," rather than "heat wave" was used to denote hot and humid conditions that include those that are less extreme (e.g., a heat index above 32°C) than what would typically be associated with heat-wave conditions in Mid-Western and Mid-Atlantic cities in the United States. This lower cut-off value was chosen for this study because the Toronto–Windsor corridor does not reach the temperature extremes found in regions of the United States.

In addition to apparent temperature, we created variables to measure the onset and duration of heat-stress episodes. Past research has shown that heat waves occurring early in the summer season have a greater impact on mortality than those of similar in-

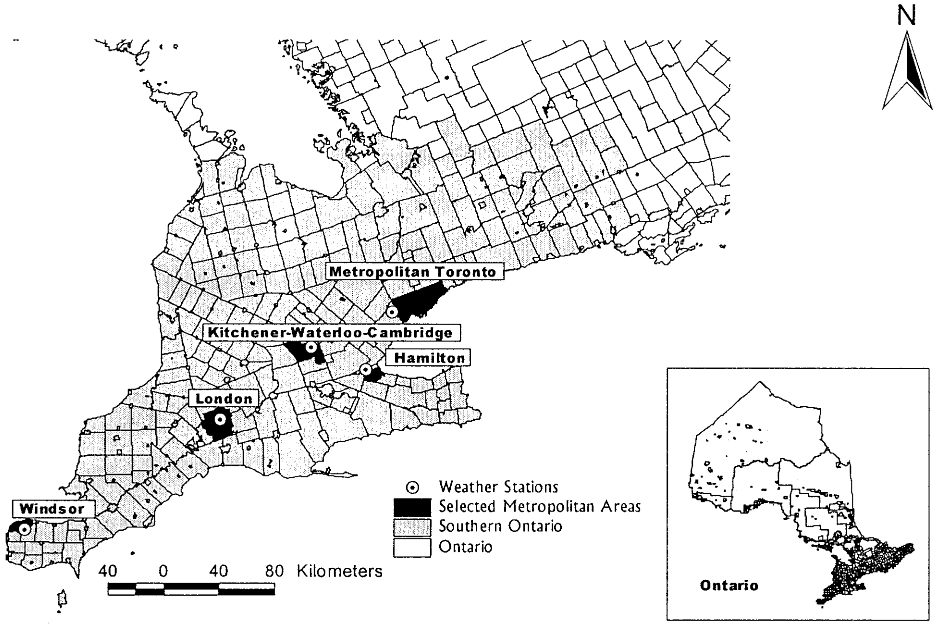


Fig. 1 The Toronto–Windsor corridor study area and weather stations

tensity occurring later in the season (Greenberg et al. 1983; Kalkstein 1991; Kalkstein and Smoyer 1993b). To investigate the effect of heat-stress onset, a dummy variable was created, based on the number of each day of the summer season from 1 (for 1 June) to 92 (for 31 August).

To measure the duration of heat-stress episodes, we used two variables. One measures the position of a given day within a consecutive string of days with T_{app} above 32°C, and the other measures the number of hours per day with an T_{app} above 32°C (HSH). The HSH variable requires 24-h data and thus was only used for cities represented by the Toronto, London, or Windsor weather stations.

Daily mortality data were obtained from Statistics Canada. Mortality from many different causes increases during heat-stress periods, and heatstroke is often under-reported as a cause of death (Kilbourne 1989). Therefore, all non-accidental causes of death were used, rather than only those that are directly related to heat. The daily number of elderly deaths was standardized by the development of a between-years standardization method to account for declining mortality rates over the study period. Statistics Canada census data, available every 5 years (1976, 1981, 1986, 1991, and 1996) were used to establish the baseline elderly populations for calculating rates. For each year in the study period, we used the same population denominator. In intervening (non-census) years, we estimated population size on the basis of an exponential growth function following Palmore and Gardner (1983):

$$e^{rt} = \frac{(\textit{population at year } t)}{(\textit{population in initial year})} \tag{2}$$

where r=rate of change and t=number of years.

The equation was solved for r using consecutive census populations (e.g., 1976 and 1981, and then 1981 and 1986, and so on). This method interpolates inter-census populations using growth rates specific to each inter-census period. Population-standardized mortality rates, which are commonly employed in many other studies, do not take into account changes in mortality rates over time that reflect non-climatic health trends. As a result, a between-years standardization procedure was used to remove inter-annual trends from mortality rates by fitting a regression line through the mean annual summer mortality rates for each of the 17 years in the study period. Regression lines were fit for each city separately.

On the basis of regression-fitted values, we used the difference between observed and expected mortality rates for each day (i.e., daily residuals) instead of mortality rates. Between-years standardization was calculated as follows:

$$\text{Between-years standardized mortality } (i,j,k) = \text{mortality}(i,j,k) - \text{predicted mortality } (j,k) \tag{3}$$

where i=day (1 June–31 August), j=summer season (1980–1996), and k=city or census subdivision (CSD). This method compensates for the decline in mortality rates that was observed over the period in all cities except London and KWC.

An excess mortality method was used to investigate heat-stress/mortality relationships on the basis of the between-years standardized mortality for each city. Excess mortality attributed to heat-stress for each city was derived by taking the mean of daily between-years standardized mortality for days classified as heat-stress days over the whole period and comparing this value to the mean daily mortality on non-heat-stress days. Because the study hypothesis was that mortality was *greater* (rather than merely different) on heat-stress days than on non-heat-stress days, a one-tailed, unpaired t-test was used to evaluate statistical significance. The strength of heat-stress/mortality relationships in the Toronto–Windsor corridor can be assessed by comparing the value of t for each city. However, because the between-years standardized mortality treatment is specific to each place, neither the magnitude of mortality on heat-stress days nor the difference in means between heat-stress and non-heat-stress days should be compared among places.

Past research has implicated factors such as population density and low income levels in mortality risk during heat waves (Buechley et al. 1972; Smoyer 1998a,b). As a means of investigating the role of possible non-climatic factors in heat-stress mortality in the Toronto–Windsor corridor, each city was described in terms of its social and urban character. We characterized housing, urban morphology, demographic composition, and socioeconomic conditions, using several indicators from the 1981, 1986, 1991 and 1996 Statistics Canada censuses. These profiles contextualize the results of the heat-stress/mortality analyses.

Results

Toronto Pearson station recorded the greatest range of mean temperatures over the study period. All stations reported their highest mean maximum air temperature during the summer of 1988. Mean apparent temperatures were relatively similar across all weather stations in the study area. In Windsor, London, and Toronto, the highest heat index (T_{app}) occurred in 1995, rather than 1988 (Table 2). For Waterloo and Hamilton, however, the summer of 1988 had the most severe apparent temperature as well as the highest mean maximum temperature. Windsor station recorded the highest percentage of heat-stress days and the greatest average number of heat-stress days per summer, more than twice the number found at Waterloo. The number of hours with a temperature above 32°C (HSH) was more than two times greater for Windsor than for London or Toronto. Overall, the Windsor station recorded the highest maximum, minimum, and apparent temperatures. In addition, the Windsor station had the longest consecutive run of heat-stress days, double the number recorded at the London or Toronto stations.

Mean daily elderly death rates ranged from a low of 11.4/100 000 seniors for Metropolitan Toronto to a high of 13.35/100 000 in Windsor (Table 3). Cities with high mean mortality rates for the elderly do not necessarily exhibit heightened sensitivity to heat-stress. In fact, during heat-stress days, Windsor had the highest elderly mortality rates of the five cities, yet the rates on these days were not statistically significantly higher than those on non-heat-stress days (results not shown). These findings illustrate the importance of using *excess* rather than total mortality to identify sensitivity to heat-stress.

Heat-stress/mortality relationships among the elderly, based on the significance level of the difference between mean daily heat-stress mortality and mean daily non-heat-stress mortality, adjusted using the between-years standardization method, were strongest in Metropolitan Toronto, Hamilton and London, followed by KWC and Windsor (Table 3). The difference of means tests reveal that mean mortality was higher on heat-stress days than on non-heat-stress days for all cities, but this relationship was not statistically significant (at the 0.05 level) for Windsor.

Daily time series of deaths and apparent temperature illustrate the association between the onset of heat-stress and its intensity and duration, and mortality. For example, in the summer of 1988, in London the correlation between deaths per day among the elderly and T_{app} is significant at the 0.05 level (r=0.23), but the relationship

Table 2 Description of weather in the Toronto–Windsor corridor. The stations at Waterloo and Hamilton do not have complete 24-h weather data. T_{min} mean minimum air temperature, T_{max} mean maximum air temperature, T_{app} apparent temperature, *HSH* heat stress hours number of hours with T_{app}>32 °C, *heat stress* number of days with T_{app}>32 °C

Parameter	Windsor 42°16′N, 82°58′W	London 42°59′N, 81°13′W	Waterloo 42°27′N, 80°23′W	Hamilton 43°16′N, 79°54′W	Toronto 43°40′N, 79°38′W
Mean minimum air temperature (T_{min}, °C)	16.9	14.3	–	–	14.3
Mean maximum air temperature (T_{max}, °C)	26.2	24.6	23.6	24.6	24.8
Year with highest mean (T_{max})	1988	1988	1988	1988	1988
Mean T_{app} (°C) [% days T_{app}>32°C]	27.5 [20.4]	25.6 [11.6]	24.6 [9.5]	25.6 [11.3]	25.4 [11.7]
Year with highest mean T_{app}	1995	1995	1988	1988	1995
Mean occurrence of heat-stress days/year [mean HSH/year]	18.9 [136.3]	10.7 [63.5]	8.7 [–]	10.4 [–]	10.8 [68.1]
Longest consecutive period of T_{app} (days) [year of occurrence]	14 (1995)	8 (1987)	7 (1987)	7 (1987)	7 (1987)

Table 3 Heat-stress mortality relationships for the elderly (over 64 years old) in the Toronto-Windsor corridor

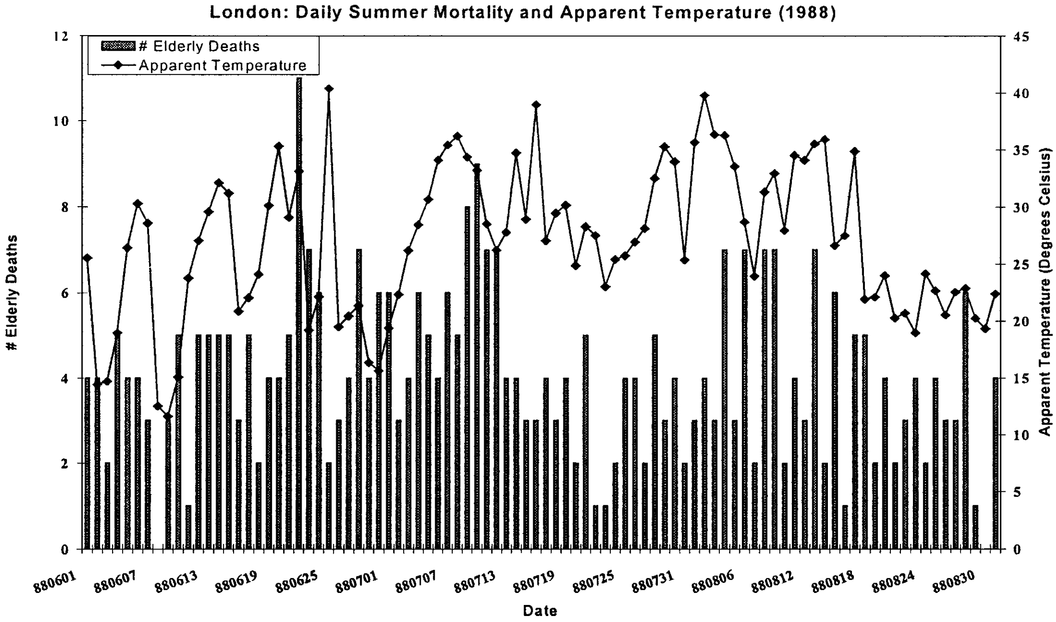
City	Mean daily deaths	Mean daily death rate[a]	Mean standardized daily heat-stress mortality (M_{HS})	Mean standardized daily non-heat-stress mortality (M_{NHS})	M_{HS}–M_{NHS} *t* (*p*-value)
Windsor	3.44	13.35	0.51	–0.13	0.65 *t=1.35* (0.09)
London	3.97	12.23	1.58	–0.21	1.79 *t=3.76* (0.00)
KWC	3.72	12.22	1.11	–0.10	1.22 *t=2.02* (0.02)
Hamilton	5.29	12.50	1.20	–0.15	1.35 *t=2.92* (0.00)
Metropolitan Toronto	30.43	11.40	0.86	–0.11	0.97 *t=5.22* (0.00)

[a] Daily deaths per 100000 elderly people

between the two variables is not consistent throughout the summer (Fig. 2, top). Both onset and duration appear particularly important. The spike in mortality on 22 June 1988 occurred on a heat-stress day (T_{app}=33°C), yet mortality did not increase dramatically with the very high heat index (T_{app}=40°C) that occurred shortly thereafter, on 25 June. This observation may be the result of "pre-shifted mortality" or "harvesting", wherein high mortality among the most vulnerable on 22 June would result in a smaller pool of susceptible persons remaining who could have died after exposure to the heat-stress conditions on 25 June.

Under more prolonged heat-stress conditions, however, T_{app} and mortality appear to be linked more closely. Deaths in London increased on 9 July 1988, 2 days after the 7 July onset of the first prolonged heat-stress episode of the season. Mortality levels decreased below the baseline of 4.07 deaths/day after this period, suggesting some pre-shifted mortality associated with the 7–11 July episode. Another heat-stress period occurred on 2–6 August. Deaths among the elderly increased, but not to the levels of the first heat-stress period. Thus mortality in London in 1988 appears to be associated with a combination of early onset and prolonged heat-stress conditions.

The temporal correlation between apparent temperature and mortality in Windsor was lower than that in London (*r*=0.11) and not significant at the 0.05 level.



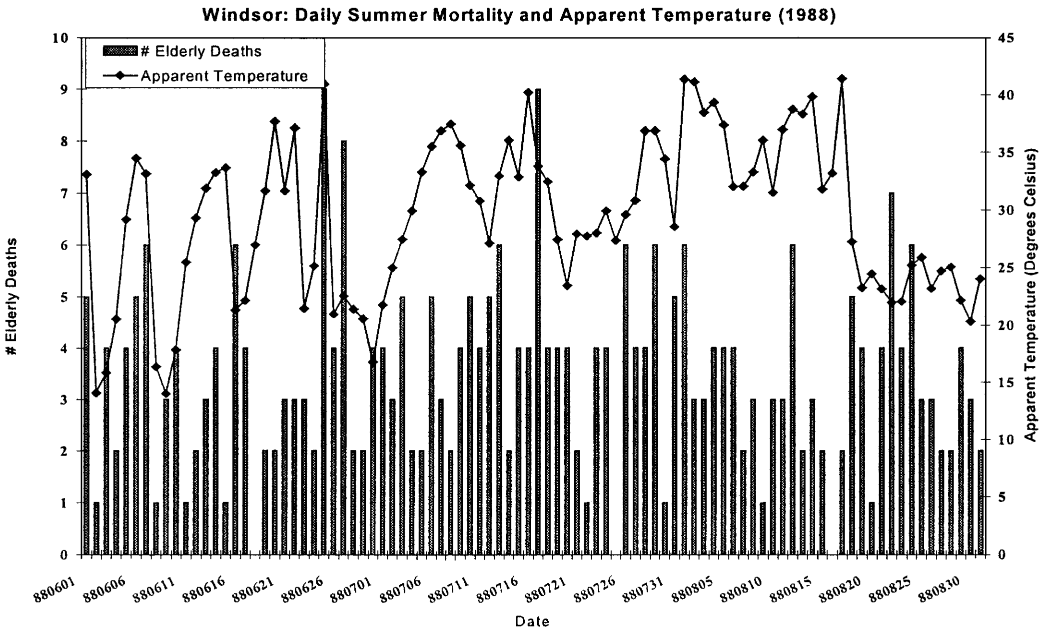


Fig. 2 Daily time-series of summer mortality and apparent temperature in London (*top*) and Windsor (*bottom*) for 1988

The correlation analysis of the entire study period, however, showed that the time of the summer when heat-stress occurred was significantly associated with mortality in Windsor (Table 4). Deaths of the elderly in Windsor were quite high on several days with high apparent temperatures earlier in the season, such as 22 June. However, the association was inconsistent, weakening later in the summer season (Fig. 2, bottom).

The weather variables having the strongest association with mortality were not consistent for each city. The small number of daily deaths (approximately 3) in London, KWC and Windsor (Table 3) may have influenced the results in these smaller cities, as minor variations in mortality can significantly modify the observed relationship. In Toronto, heat-stress duration [as measured in days and hours (HSH)] had a relatively strong correlation with mortality (Table 4). The date of heat-stress onset was important in London and Hamilton, yet was not significant at the 0.05 level in Toronto or KWC. For all cities but Windsor, the heat-stress days (T_{app}>32°C), apparent temperature, and maximum temperature were significantly correlated with mortality. Minimum temperature had a lower correlation with mortality than maxi-

Table 4 Correlation of selected daily weather variables and mortality

City	Heat-stress day[a]	T_{app}	T_{max}	Date of onset[b]	Heat stress duration[c]	T_{min}[d]	HSH[e]
Windsor	0.035	0.029	0.035	–0.134*	0.038	0.028	0.037
London	0.091*	0.085*	0.080*	–0.147*	0.103*	0.055*	0.093*
KWC	0.056*	0.070*	0.064*	–0.095	0.039	–	–
Hamilton	0.077*	0.098*	0.103*	–0.173*	0.077*	–	–
MetropolitanToronto	0.146*	0.136*	0.130*	–0.115	0.151*	0.128*	0.151*

* Significant at P <0.05
[a] Dichotomous variable where 0 = T_{app}≤32 °C, and 1 = T_{app}>32 °C
[b] Time of the summer (1=1 June, 92=31 August) when heat-stress day occurred (this variable has been correlated only with daily mortality on heat-stress days)
[c] Number of consecutive heat-stress days
[d] Data were unavailable for KWC and Hamilton
[e] Hours with T_{app}>32 °C in a heat-stress day. Data were unavailable for KWC and Hamilton

Table 5 Summary of heat-stress mortality relationships and census characteristics. The categorization is based on each city relative to all other cities in the Toronto–Windsor corridor study area

City	Strength of heat-stress/mortality relationship[a]	Degree of urbanization	Percentage of seniors	Incidence of low income[b]	Cost of living	Percentage of older housing[c]
Windsor	Not significant	Low	High	Moderate	Low	High
London	Very strong	Moderate	Low	Low	Moderate	Low
KWC	Moderate	Low	Low	Low	Low	Low
Hamilton	Strong	High	High	High	High	High
Metropolitan Toronto	Very strong	High	Moderate	High	High	Moderate

[a] Strength of relationship based on t value where t≤1.65=not significant; 1.65<t≤1.96=weak; 1.96<t=2.56=moderate; 2.56<t=3.29=strong; and t >3.29=very strong
[b] Incidence of low income was unavailable for 1981
[c] Housing built before 1946

mum temperature or apparent temperature in both Toronto and London, and was not significant in Windsor.

Variation in the urban, socioeconomic, and demographic structure of the cities in the Toronto–Windsor corridor is considerable. Toronto and Hamilton are the most urbanized, Windsor and KWC are the least urbanized, and London falls in the middle. Windsor and Hamilton have the highest concentration of older dwellings, KWC and London have the lowest, and Metropolitan Toronto has a moderate level of older housing (Table 5). Windsor and Hamilton also have the highest percentage of seniors, London and KWC have the lowest percentage, and Toronto has a moderate percentage of people 65 years and older. The cost of living has fluctuated over the study period, but in 1991 and 1996 Metropolitan Toronto and Hamilton had the highest costs of living, Windsor and KWC had the lowest, and London had a moderate cost of living. On the basis of 1991 and 1996 data, Hamilton and Toronto had the highest incidence of low income, London and KWC the lowest, and Windsor a moderate incidence of low income (Table 5).

The difference of means tests and Pearson's correlation coefficients consistently identified the strongest heat-stress/mortality relationships in Metropolitan Toronto and London, followed by Hamilton. Census data on population, housing, and socioeconomic conditions reveal some similarities among these cities, but differences as well. For example, all three cities have relatively high levels of urbanization and a moderate to high cost of living (Table 5), while the incidence of low income was low in London and high in Hamilton and Toronto. We also noted different heat-stress-related mortality levels in cities with relatively similar housing and economic histories. For example, Windsor has the greatest percentage of dwellings built before World War II, followed by Hamilton, and manufacturing is the leading source of employment in both cities (Statistics Canada 1994; 1998). The two cities, nevertheless, had markedly different levels of excess mortality. The incidence of low income and the percentage of elderly residents also did not appear to be related to heat-stress mortality.

Discussion

The results of this research reveal that heat-stress mortality varies among places with relatively similar weather conditions. These findings illustrate the importance of non-climatic factors in mediating the effect of summer weather on human health, and provide information about the ability of the Toronto–Windsor corridor's population to adapt to heat-stress conditions. The largest uncertainty lies in identifying which specific non-climatic factors are the most important. The results of the analysis implicate urbanization as a potential risk factor in heat-stress mortality. This finding corresponds with the results of studies of heat-related mortality in the United States (Buechley et al. 1972; Smoyer 1998a,b). Urban areas experience higher temperatures than less built-up areas, particularly at night when buildings and paved areas continue to emit long-wave radiation. The lack of a respite from heat-stress conditions at night has been thought to be particularly dangerous to human health (Kilbourne et al. 1982). As urban development continues in the Toronto–Windsor corridor, population vulnerability to heat-stress is likely to increase.

The effect of demographic composition and socioeconomic conditions on vulnerability to heat-stress is less clear than that of urbanization. Demographic and socioeconomic characteristics did not appear to be consistently associated with the strength of the heat-stress/mortality relationship. Among the cities with very strong relationships, London had a low percentage of seniors and incidence of low income and a moderate cost of living, while Metropolitan Toronto had a moderate percentage of seniors along with a high cost of living and incidence of low income. Hamilton ranked high on all three of these variables. KWC and Windsor, which had the weakest heat-stress/mortality relationships, had the lowest costs of living. Thus, it appears that heat-stress mortality is not a function of the age structure of the population, but that socioeconomic factors are important. These findings correspond with the results of studies in the United States that have demonstrated a relationship between poverty and mortality risk during heat waves (Buechely et al. 1972; Kilbourne et al. 1982; Smoyer 1998b). It is notable that cost of living has a stronger association with heat-stress mortality than the incidence of low income in the Toronto–Windsor corridor. Elderly people residing in cities with lower costs of living are likely to have larger disposable incomes that can provide them with more options for avoiding heat-stress, such as air conditioning.

Given the more frequent exposure to heat-stress conditions in Windsor, we initially expected to see a stronger heat-stress/mortality relationship in this city. There are several potential explanations for this not being recorded. The small population and relatively low number of elderly deaths per day (approximately 3.4) in Windsor may have affected our ability to isolate a statistically significant heat-stress/mortality relationship. However, we hypothesize that non-climatic variables, such as protective behaviors, population density, and air conditioning, rather than an insufficiently robust statistical procedure, account for the lack of a heat-stress/mortality effect in Windsor. For example, in 1981, the population density of Windsor's urban core was the lowest among 27 Canadian cities (Bourne 1989). Windsor also consistently had the greatest percentage of single-family detached dwellings during the study period (Statistics Canada 1983, 1987, 1994, 1998). Unfortunately, air conditioning data for the five cities in this study are not readily available, and we have not yet been able to investigate differences in air conditioning availability among the cities studied. This, however, is an important area for future study.

In addition to the role of air conditioning, the association between heat-stress mortality in the Toronto–Windsor corridor and demographic composition, socioeconomic characteristics, and urban structure may also be confounded by unmeasured variables such as air pollution. A large body of literature has illustrated the harmful effects of air pollution on health (e.g., Choi et al. 1997; Katsouyanni et al. 1993; Burnett et al. 1998a,b; Smoyer et al. 2000). Further analysis of heat-stress in the Toronto–Windsor corridor would benefit from the addition of air pollution data.

An important question arising from our research is how population vulnerability and adaptation to climate change may vary within the Toronto–Windsor corridor. The results suggest that vulnerability to increases in heat-stress induced by climate change will be greatest among elderly urban dwellers, particularly in cities with a high cost of living. Changes in demographic composition must be considered along with changes in the climate of this area. As the Canadian population ages, a greater number of people will enter the high-risk group, and thus we expect to see increases in the number of deaths during heat-stress events. Therefore, high-risk cities with larger numbers of elderly residents, such as Hamilton and Metropolitan Toronto, are most in need of policies that reduce vulnerability and increase the potential for adaptation.

In summary, heat-stress mortality among the elderly varied within the Toronto–Windsor corridor despite relatively similar weather within the region. The more densely populated cities of Toronto, London, and Hamilton had the strongest relationships, while the relationship in lower-density Windsor was not statistically significant. Although minor differences in summer weather variability may account for the variation in the strength of the relationships identified, non-climatic factors such as urbanization and cost of living also appear to be important.

Heat-stress conditions are predictable, and heat-stress mortality is preventable. A combination of hot weather watch/warning systems, well-organized plans for responding to heat emergencies, and ongoing education about precautions against heat-stress is likely to be useful in reducing the harmful impacts of heat-stress conditions on health. Toronto and Hamilton have begun to put such measures in place, but their effectiveness has not yet been formally evaluated. These public health measures are also important early steps for adaptating to climate change. We emphasize, however, that such efforts to promote awareness of heat stress and prevent mortality, which require behavioral changes at the individual level, are insufficient without public health measures aimed at reducing vulnerability and increasing the adaptability and adaptive capacity of the population as a whole. We recommend that attention be given to reducing vulnerability to heat-stress and enhancing adaptability in the Toronto–Windsor corridor. For example, policies should focus on (1) promoting wise land use so as to minimize the effects of urban heat islands and provide vegetated and ventilated areas to facilitate cooling, and (2) ensuring that health and social services are readily available to populations in need.

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References

Bourne LS (1989) On the spatial structure of metropolitan areas in Canada: a discriminant analysis. University of Toronto: Centre of Urban and Community Studies. Research paper no 172

Buechley RW, Van Bruggen J, Truppi LE (1972) Heat island equals death island? Environ Res 5:58–92

Burnett RT, Çakmak S, Brook JR (1998a) The effect of the urban ambient air pollution mix on daily mortality rates in 11 Canadian cities. Can J Public Health 89: 152–156

Burnett RT, Çakmak S, Raizenne ME, Steib D, Vincent R, Krewski D, Brook JR, Philips O, Ozkaynak H (1998b) The association between ambient carbon monoxide levels and daily mortality in Toronto, Canada. J Air Waste Manage Assoc 48: 689–700

Choi K, Inoue S, Shinozaki R (1997) Air pollution, temperature and regional differences in lung cancer mortality in Japan. Arch Environ Health 52: 160–168

Greenberg JH, Bromberg J, Reed CM, Gustafson TL, Beauchamp RA (1983) The epidemiology of heat-related deaths, Texas – 1950, 1970–79, and 1980. Am J Public Health 73:805–807

Kalkstein LS (1991) A new approach to evaluate the impact of climate on human mortality. Environ Health Perspect 96:145–150

Kalkstein LS, Davis RE (1989) Weather and human mortality: an evaluation of demographic and interregional responses in the United States. Ann Assoc Am Geog 79:44–64

Kalkstein LS, Smoyer KE (1993a) The impact of climate change on human health: some international implications. Experientia 49:969–979

Kalkstein LS, Smoyer KE (1993b) The impact of climate on Canadian mortality: present relationships and future scenarios. Environment Canada/Canadian Climate Center Report no 93–7 50

Katsouyanni K, Pantazopoulou A, Touloumi G, Tselepidaki I, Moustris K, Asimakopolous D, Poulopoulou G, Trichopoulos D (1993) Evidence for interaction between air pollution and high temperature in the causation of excess mortality. Arch Environ Health 48:235–242

Kilbourne EM (1989) Heat waves. In: Gregg MB (ed) The public health consequences of disasters 1989. CDC, US Department of Health and Human Services, Atlanta, pp 51–61

Kilbourne EM, Choi K, Jones TS, Thacker SB, Field Investigation Team (1982) Risk factors in heat stroke: a case-control study. JAMA 247:3332–3336

National Climatic Data Center (1999) Billion dollar US weather disasters 1980–1999. Website http://wwwncdcnoaagov/ol/reports/billionzhtml

Palmore JA, Gardner RW (1983) Measuring mortality fertility and natural increase: a self-teaching guide to elementary measures. East-West Center, Honolulu

Smoyer KE (1998a) A comparative analysis of heat waves and associated mortality in St Louis, Missouri – 1980 and 1995. Int J Biometeorol 42:44–50

Smoyer KE (1998b) Putting risk in its place: methodological considerations for investigating extreme event health risk. Soc Sci Med 47:1809–1824

Smoyer KE, Kalkstein LS, Greene JS, Ye H (2000) The impacts of weather and pollution on human mortality in Birmingham, Alabama and Philadelphia, Pennsylvania. Int J Climatol (in press)

Statistics Canada (1983) Census divisions and subdivisions: population occupied private dwellings private households and census and economic families in private households – Selected social and economic characteristics Ontario. 1981 Census of Canada, catalogue number E-576, Table 1. Ministry of Supply and Services Canada, Ottawa

Statistics Canada (1987) Profiles: census divisions and subdivisions Ontario. Part 2. 1986 Census of Canada, catalogue number 94–112. Ministry of Supply and Services Canada, Ottawa

Statistics Canada (1994) Profile of census divisions and subdivisions in Ontario. Part B. 1991 Census of Canada, catalogue number 95–338, Table 1. Industry Science and Technology Canada, Ottawa

Statistics Canada (1998) Profile of census divisions and subdivisions in Ontario. 1996 Census of Canada, catalogue number 95–187-XPB. Ministry of Industry Canada, Ottawa

Steadman RG (1979) The assessment of sultriness part I. A temperature-humidity index based on human physiology and clothing science. J Appl Meteorol 18:861–873

Steadman RG (1984) A universal scale of apparent temperature. J Climate Applied Meteorol 23:1674–1687