Int J Biometeorol (2012) 56:605–619
DOI 10.1007/s00484-011-0449-y

ORIGINAL PAPER

Climate change and future temperature-related mortality in 15 Canadian cities

Sara Lauretta Martin · Sabit Cakmak · Christopher Alan Hebbern · Mary-Luyza Avramescu · Neil Tremblay

Received: 14 October 2010 / Revised: 3 May 2011 / Accepted: 3 May 2011 / Published online: 20 May 2011

Abstract The environmental changes caused by climate change represent a significant challenge to human societies. One part of this challenge will be greater heat-related mortality. Populations in the northern hemisphere will experience temperature increases exceeding the global average, but whether this will increase or decrease total temperature-related mortality burdens is debated. Here, we use distributed lag modeling to characterize temperature-mortality relationships in 15 Canadian cities. Further, we examine historical trends in temperature variation across Canada. We then develop city-specific general linear models to estimate change in high- and low-temperature-related mortality using dynamically downscaled climate projections for four future periods centred on 2040, 2060 and 2080. We find that the minimum mortality temperature is frequently located at approximately the 75th percentile of the city's temperature distribution, and that Canadians currently experience greater and longer lasting risk from cold-related than heat-related mortality. Additionally, we find no evidence that temperature variation is increasing in Canada. However, the projected increased temperatures are sufficient to change the relative levels of heat- and cold-related mortality in some cities. While most temperature-related mortality will continue to be cold-related, our models predict that higher temperatures will increase the burden of annual temperature-related mortality in Hamilton, London, Montreal and Regina, but result in slight to moderate decreases in the burden of mortality in the other 11 cities investigated.

Electronic supplementary material The online version of this article (doi:10.1007/s00484-011-0449-y) contains supplementary material, which is available to authorized users.

S. L. Martin · S. Cakmak (✉) · C. A. Hebbern · N. Tremblay
Population Studies Division, Environmental Health Science and Research Bureau, HECSB, Health Canada,
50 Columbine Drive,
Ottawa, ON, Canada
e-mail: sabit.cakmak@hc-sc.gc.ca

M.-L. Avramescu
Department of Earth Sciences, University of Ottawa,
Marion Hall,
Ottawa, ON, Canada

Keywords Climate change · Cold-related mortality · Heat-related mortality · Temperature-related mortality · Temperature variation

Introduction

The potential effects of climate change on human health are wide-ranging and serious (Epstein 2005; Costello et al. 2009; Baer and Singer 2009). Areas of concern include increased malnutrition and starvation due to destabilization of food supplies, increased vector-borne disease, and increased heat-related mortality (McMichael 1993; Meehl and Tebaldi 2004; McMichael et al. 2006). Indeed, Campbell-Lendrum et al. (2003) estimated that, relative to a 1961–1990 baseline, climate change caused a loss of 5.5 million disability-adjusted life years through malaria, diarrheal disease, malnutrition, floods and heat waves in 2000 alone.

Several recent heat waves in Canada, the United States, and in Europe have emphasized human susceptibility to high ambient temperatures and increased interest in how future warmer temperatures will alter temperature-related mortality (Eurowinter Group 1997; Epstein 2005; Hajat et al. 2006; Le Terte et al. 2006; Kovats and Hajat 2008; Robine et al. 2008). Similarly, the high cold-related mortality in some countries is a reminder of the continued human susceptibility to low temperatures—a risk that may be underappreciated (Keatinge et al. 2000; Healy 2003; Mercer 2003; Díaz et al. 2005; Hassi 2005). Biologically, temperature stress may have an indirect but causal relationship with a variety of causes of death beyond hypo- and hyperthermia. Temperature stress can induce a variety of physiological changes in circulation patterns and respiratory rate, which in turn may exacerbate underlying conditions and result in increased mortality from a range of cardiovascular and respiratory diseases (Bull and Morton 1978; Basu and Samet 2002; Keatinge and Donaldson 2004; Havenith 2005; Kolb et al. 2007). However, while the association between meteorological conditions and increased morbidity and mortality has been established by a large body of literature (reviewed by Basu and Samet 2002; Gosling et al. 2009a), the effect of climate change on the overall burden of temperature-related mortality is uncertain (McMichael et al. 2006). For example, it has been suggested that milder winters will reduce cold-related mortality, offsetting increases in heat-related mortality; however, predictions for developed countries have been mixed in direction and magnitude, with some predicting overall increases (Langford and Bentham 1995; Kalkstein and Greene 1997; Duncan et al. 1997; Guest et al. 1999; Knowlton et al. 2007; Medina-Ramón and Schwartz 2007; Doyon et al. 2008), some predicting declines (Martens 1998; Donaldson et al. 2001; Keatinge et al. 2000), and others predicting little change (Davis et al. 2004).

Climate change models suggest that Canadian cities will experience greater-than-average increases in temperature (Weaver 2004). Furthermore, previous work has indicated that locations with mild warm seasons show the largest increases in mortality due to extreme heat (Lemmen and Warren 2004; Medina-Ramón and Schwartz 2007). These concerns were heightened by the 2006 Canadian heat wave during which Toronto recorded its highest temperature and 780 people are estimated to have died directly from the heat (Baer and Singer 2009). Additionally, researchers have predicted an increased frequency of high temperatures and heat waves in the future, beyond that expected from a shift in mean temperature, because of increased temperature variation (Katz and Brown 1992; Meehl et al. 2001; Schär et al. 2004). Here, we estimate the effect of climate change on annual temperature-related mortality burdens for 15 Canadian cities. We use distributed lag and generalized linear models to characterize current temperature–mortality relationships for each city using observed daily non-accidental mortality and daily temperature data from 1981 to 2000 and we examine historical change in temperature variance across Canada. We then use these models and high-resolution dynamically downscaled future temperatures produced by the Climate Simulation Team at the Ouranos Consortium (Music and Caya 2007) to predict changes in annual mortality burdens for the 20-year periods surrounding 2040, 2060, and 2080.

Materials and methods

Data

Daily non-accidental mortality data from 1981 to 2000 for Calgary, Alberta; Edmonton, Alberta; Halifax, Nova Scotia; Hamilton, Ontario; London, Ontario; Montreal, Quebec; Quebec City, Quebec; Regina, Saskatchewan; Saint John's, Newfoundland; Saskatoon, Saskatchewan; Toronto, Ontario; Vancouver, British Columbia; Windsor, Ontario; and Winnipeg, Manitoba were obtained through the Public Health Agency of Canada from the Canadian Vital Statistics databases at Statistics Canada with the knowledge and consent of the Provincial and Territorial Vital Statistics Registrars which supply the data to Statistics Canada. Their cooperation is gratefully acknowledged. Non-accidental causes of death for 1981 to 1999 were categorized using codes from the International Classification of Diseases 9th revision (codes <800). Cause-of-death coding changed for the 2000 data to the International Classification of Diseases 10th revision, where codes A00 to R99 represent non-accidental mortality [World Health Organization (WHO) 2007]. Mortality rates per 100,000 were calculated by dividing the number of deaths recorded each day by Statistics Canada's annual population estimate for the city, and multiplying by 100,000.

Observed meteorological data for each city were obtained from Environment Canada's online database for 1981 to 2000. Modeled monthly mean temperatures for 1961–2100 were obtained from the Canadian Centre for Climate Modeling and Analysis. These data were generated by the Climate Simulation Team at the Ouranos Consortium using the Canadian Regional Climate Model (CRCM4) (Scinocca and McFarlane 2004; Music and Caya 2007). The simulations were run with parameters from the A2 climate scenario, which is 1 of 40 equally plausible future scenarios outlined by the Intergovernmental Panel on Climate Change. Within these scenarios, the A2 storyline predicts an intermediate level of warming (Nakićenović and Swart 2000; Pielke et al. 2008; Costello et al. 2009; Schneider 2009). For each city, the average of predicted temperature values for the 45-km square closest to the local airport, and eight adjacent squares were used to represent the local future conditions. We estimated monthly anomalies following Gosling et al. (2009b) by calculating the difference between the monthly temperatures from the modeled baseline period of 1981–2000 (Doyon et al. 2008; Gosling et al. 2009b), using 5-year groupings of future temperatures to create a smooth increase in temperature. For each city and month, the monthly anomalies were added to the observed daily temperature series for 1981–2000 to represent the future daily temperature series. For example, the modeled monthly temperature for Toronto for July 1981 to 2000 was 21.0°C. This was subtracted from the modeled July 2031 to 2035 temperature, 22.4°C, producing an anomaly, +1.4°C. This anomaly was added to the observed daily temperature series for July 1981, creating a daily predicted temperature series for July 2031. The use of this "delta" method limits the effect of model bias on the predicted temperature series (Déqué 2007; Gosling et al. 2009b).

We examined the historical change in the standard deviation of average, maximum summer and minimum winter temperatures in Canada using homogenized temperature series (Vincent et al. 2002) with the intent to extrapolate future change in variance. We bootstrapped calculations of the standard deviation of 5-year periods of the homogenized temperature data from 56 locations across Canada. Periods where more than 5% of the data were missing were treated as missing. The series considered had a maximum length of 110 years for a total of 22 five-year periods. Where possible, we used data from the cities examined in this study, but not all cities had data available. We then conducted trend analysis on the standard deviations using Kendall's tau.

Modeling

Our approach to statistical modeling of current temperature–mortality relationships had three steps: (1) removal of the secular trends; (2) analysis of the lag structure for temperature-related mortality for each city; and (3) developing "cold" and "hot" temperature models for each city. Models were developed using even-year data, so that odd-year data could be used to test the model performance.

To remove secular trends, we assumed a Poisson distribution and tested natural splines of time, season and year with 1–120 degrees of freedom (*df*), and factors for year, month and day of the week. As with all model choices, Akaike's Information Criterion (AIC) (Akaike 1973), tests indicating whether the residuals from the model were white noise, and the partial autocorrelations, were used to inform both the choice of a natural spline of time with 15 *df* (1.5 *df*/year) and a factor for year to remove secular trends from the 10-year period. The effect of altering the number of degrees of freedom in this model or adding a binary indicator of deaths from viral respiratory conditions such as influenza was tested. The residual mortality rates following secular trend removal were used in the construction of the distributed lag models and the general linear models.

The full temperature–mortality relationship for each city was modeled using distributed lag non-linear modeling (Gasparrini and Armstrong 2010). Distributed lag models, which here assumed a Poisson distribution, allow effects to persist to the full period, but do not constrain them to do so (Schwartz 2000; Braga et al. 2001, 2002; Doyon et al. 2008; Gasparrini and Armstrong 2011). We tested maximum, minimum, and average temperature as well as two composite measures of temperature and humidity, apparent temperature and humidex, with up to 35 days of lag in the distributed lag models. We also examined the effect of potential confounders including specific humidity, barometric pressure and diurnal temperature change, as well as factors describing hot and cold temperature thresholds. However, like Barnett et al. (2010), we found that different measures of temperature exposure were highly correlated and produced similar results. The final composition of the distributed lag model was a natural spline of average temperature with 4 *df* for temperature and 3 *df* for lag.

The distributed lag models were used to evaluate several characteristics of the temperature–mortality relationships. The minimum mortality temperature (MMT) (Curriero et al. 2002) for each city was estimated as the positive temperature corresponding to the lowest modeled mortality rate at lag 0 (Keatinge et al. 2000; Donaldson et al. 2001, 2003). This rate was used as the baseline mortality rate. Mortality displacement was evaluated by comparing the timing of the highest and lowest cumulative risks across the temperature range. The timing of the maximum cumulative risk was also used to inform the number of days lag incorporated in the general linear models of temperature-related mortality above and below the MMT. We refer to these models as the hot and cold models, respectively.

The hot and cold general linear models with log link functions assumed a Poisson distribution and were constructed for each city using natural splines of average temperature grouped over 3 days (lag_0, $lag_{1–3}$, $lag_{4–6}$, $lag_{5–9}$, $lag_{10–12}$, $lag_{13–15}$, $lag_{16–18}$, and $lag_{19–21}$) (Armstrong 2006; Doyon et al. 2008). The range of temperatures corresponding to the lowest mortality rates, less than or equal to 1% greater risk compared to the MMT, was estimated using these models. This differs from aggregating mortalities into 2 or 3°C temperature groups and selecting the band of minimum mortality used by other authors, but reflects the curve and asymmetry of the temperature–mortality relationship (Keatinge et al. 2000; Donaldson et al. 2003; Laaidi et al. 2006). As mentioned above, models were then tested by examining their ability to predict cold- and heat-related deaths in odd years, and subsequently used to predict future mortality.

Current and future excess mortality calculation

The current annual excess mortality rates due to cold and hot temperatures were estimated from the odd-year data by removing the secular trends and subtracting the baseline mortality rate. As the baseline mortality rate did not correspond to the lowest mortality rate in the data set, the result of this calculation was a series of positive excesses and negative deficits compared to the expected baseline rate. The sum of these deviations for days above and below the MMT range provided an estimate of each year's cold and hot mortality. The average of these annual rates was considered representative of current annual excess mortality rates.

The city-specific general linear models were used to predict daily deaths given the future daily temperature time series. The baseline mortality rate was then subtracted from these predictions and annual rates were calculated as above. Future changes in mortality rates were then estimated by calculating the difference between this future rate and the annual mortality rate estimated by the model using the temperature data from the even years. These anomalies were then added to the estimated annual excesses calculated from odd years of the baseline period.

All statistical analyses and modeling were completed in R version 2.10.1 (The R Foundation for Statistical Computing 2009).

Results

Current temperature–mortality relationships

The base period's annual average temperature for the 15 Canadian cities ranged from 10.3°C in Vancouver to 2.7°C in Saskatoon (Table 1). The standard deviation of temperatures for the base period ranged from 5.7°C in Vancouver to 14.1°C in Winnipeg. The daily crude mortality rate averaged 1.68/100,000 and ranged from 1.23/100,000 in Calgary to 2.20/100,000 in Windsor. Yearly rates averaged 614.5/100,000.

The non-linear distributed lag models showed the typical U-, W-, or backward-J-shaped relationship between temperature and mortality at lag 0 (read along x-axis) for 11 of the 15 cities, specifically: Calgary, Edmonton, Hamilton, London, Montreal, Ottawa, Quebec City, Regina, Toronto, Vancouver, and Windsor (Fig. 1; Supplementary Fig. 1) (Curriero et al. 2002; Doyon et al. 2008). The remaining relationships were more linear in Saskatoon and Winnipeg than in the cities mentioned above and roughly shaped like upside-down U in Halifax and Saint John's. At lag 0, the relationship at temperatures below the MMT range was flat or shallow in 7 (Calgary, Edmonton, Hamilton, Quebec City, Saskatoon, Toronto, and Winnipeg) of the 15 cities suggesting that the risk from extremely cold temperatures is similar to that from moderately cold temperatures in these cities. In three cases (Halifax, London, and Saint John's), the relationship between temperature and mortality was positive at the coldest temperatures, indicating that risk decreased at extremely cold temperatures. However, in the remaining five cities (Montreal, Ottawa, Regina, Windsor,

Table 1 Observed temperature and mortality statistics for the 15 Canadian cities included in this study and average future temperature projections

City	Population (2000)	Mortality rate[a]		Temperature 1981–2000°C				Standard deviation
		Daily	Yearly	All[b]	DJF[b]	JJA[b]	Range[c]	
Calgary	952,941	1.23	448.6	4.6	-6.3	15.4	(−33.8 to 25.5)	10.6
Edmonton	945,797	1.33	486.4	2.8	-10.7	15.2	(−38.0 to 23.8)	11.8
Halifax	366,309	1.62	590.7	6.4	-4.4	17.1	(−33.8 to 25.5)	9.5
Hamilton	678,639	1.71	622.6	8.8	-3.6	20.9	(−23.2 to 31.7)	10.7
London	449,750	2.00	730.5	8.0	-4.1	19.7	(−24.6 to 28.9)	9.7
Montreal	3,494,133	1.71	625.5	6.9	-7.4	20.0	(−14.8 to 22.8)	11.8
Ottawa	822,804	1.55	566.7	6.3	-8.2	19.6	(−14.3 to 22.9)	11.9
Quebec City	692,188	1.67	608.0	4.7	-9.9	18.1	(−16.3 to 21.1)	11.9
Regina	199,054	1.78	649.6	3.2	-13.0	17.9	(−37.6 to 31.0)	13.5
Saskatoon	230,166	1.72	629.4	2.7	-13.8	17.3	(−38.9 to 31.3)	13.7
St. John's	146,507	1.36	497.7	4.7	-3.6	13.4	(−20.9 to 26.1)	8.4
Toronto	4,761,231	1.55	564.1	8.0	-4.0	20.0	(−9.6 to 23.3)	10.4
Vancouver	2,040,295	1.77	646.3	10.3	4.1	17.0	(−1.1 to 19.0)	5.7
Windsor	314,121	2.20	804.6	9.7	-2.4	21.6	(−7.3 to 24.7)	10.4
Winnipeg	677,345	2.04	746.3	3.2	-14.1	18.6	(−22.6 to 22.1)	14.1
Average		1.68	614.5	6.0	-6.8	18.1	(−22.5 to 25.3)	10.9

[a] The daily and yearly crude mortality rates per 100,000 individuals for the 1981–2000 period

[b] Observed average temperatures in Celsius for the cities with December, January and February (*DJF*) included in the winter estimates and June, July and August (*JJA*) included in the summer estimates for the 1981–2000 period

[c] Average temperature range from minimum to maximum observed during the for the 1981–2000 period

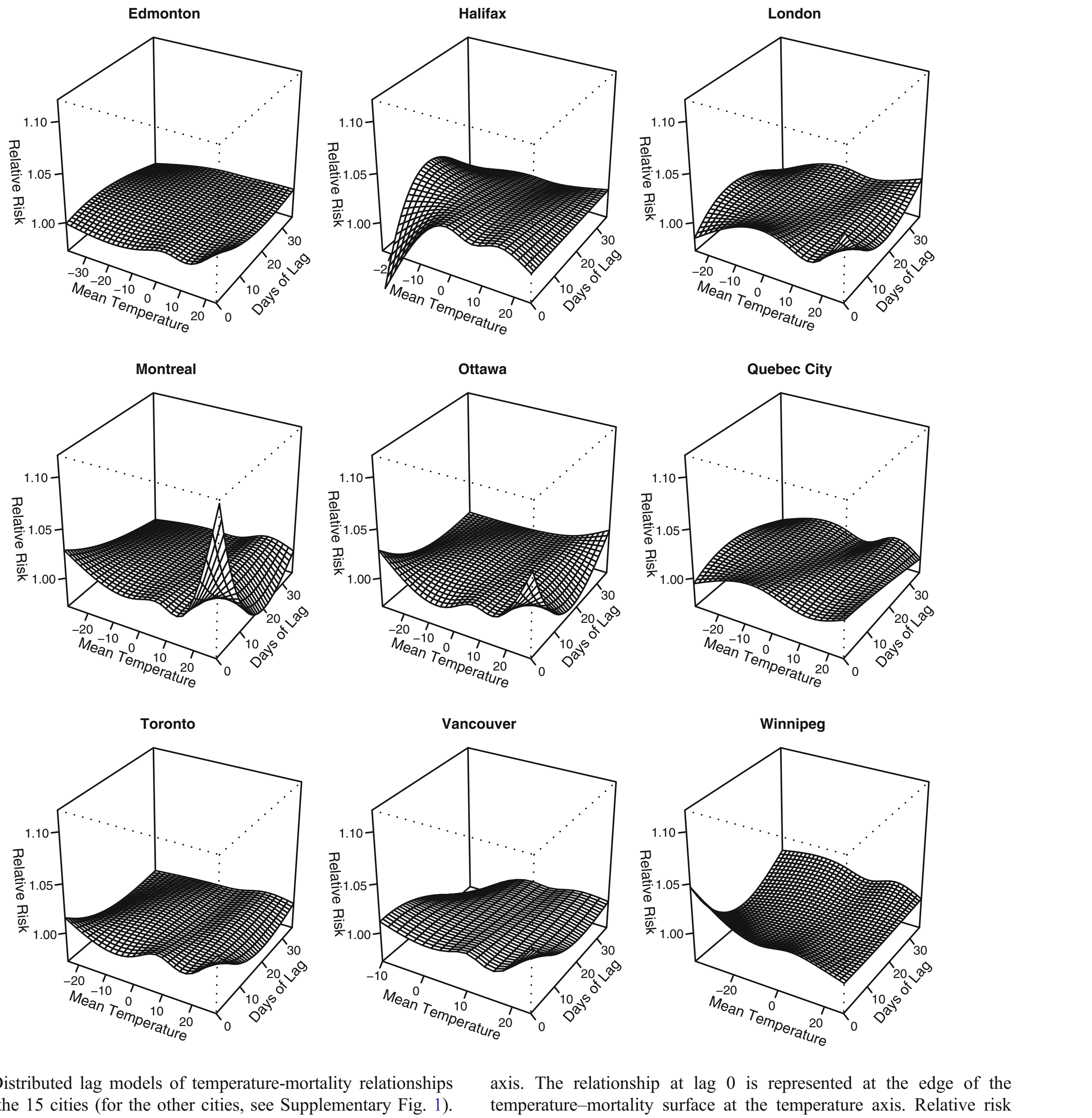

Fig. 1 Distributed lag models of temperature-mortality relationships for 9 of the 15 cities (for the other cities, see Supplementary Fig. 1). The surfaces presented show relative risk (*z*-axis) across temperature (*x*-axis) and lag to 35 days (*y*-axis). As a result, the figures can be interpreted by imagining slices parallel to either the temperature or lag axis. The relationship at lag 0 is represented at the edge of the temperature–mortality surface at the temperature axis. Relative risk estimates represent the risk of mortality at a specific temperature and lag, which was set to 1.0

and Winnipeg), the slope remained relatively steep from the MMT to the coldest temperature experienced. The slope above the MMT also varied from relatively shallow in Calgary to relatively steep in Vancouver. In four cases, Halifax, Saskatoon, Saint John's, and Winnipeg, the maximum temperature corresponded to the minimum mortality threshold, suggesting that these cities do not currently experience significant levels of heat-related mortality. Additionally, the confidence intervals for the RR estimates at the maximum temperature for Calgary included 1.0. The city-specific relationships between temperature and mortality when modeled using hot and cold general linear models were similar in shape to slices through these non-linear distributed lag surfaces, at lags corresponding to maximum cumulative relative risk (CRR) at the 5th and 95th temperature percentiles (Fig. 2).

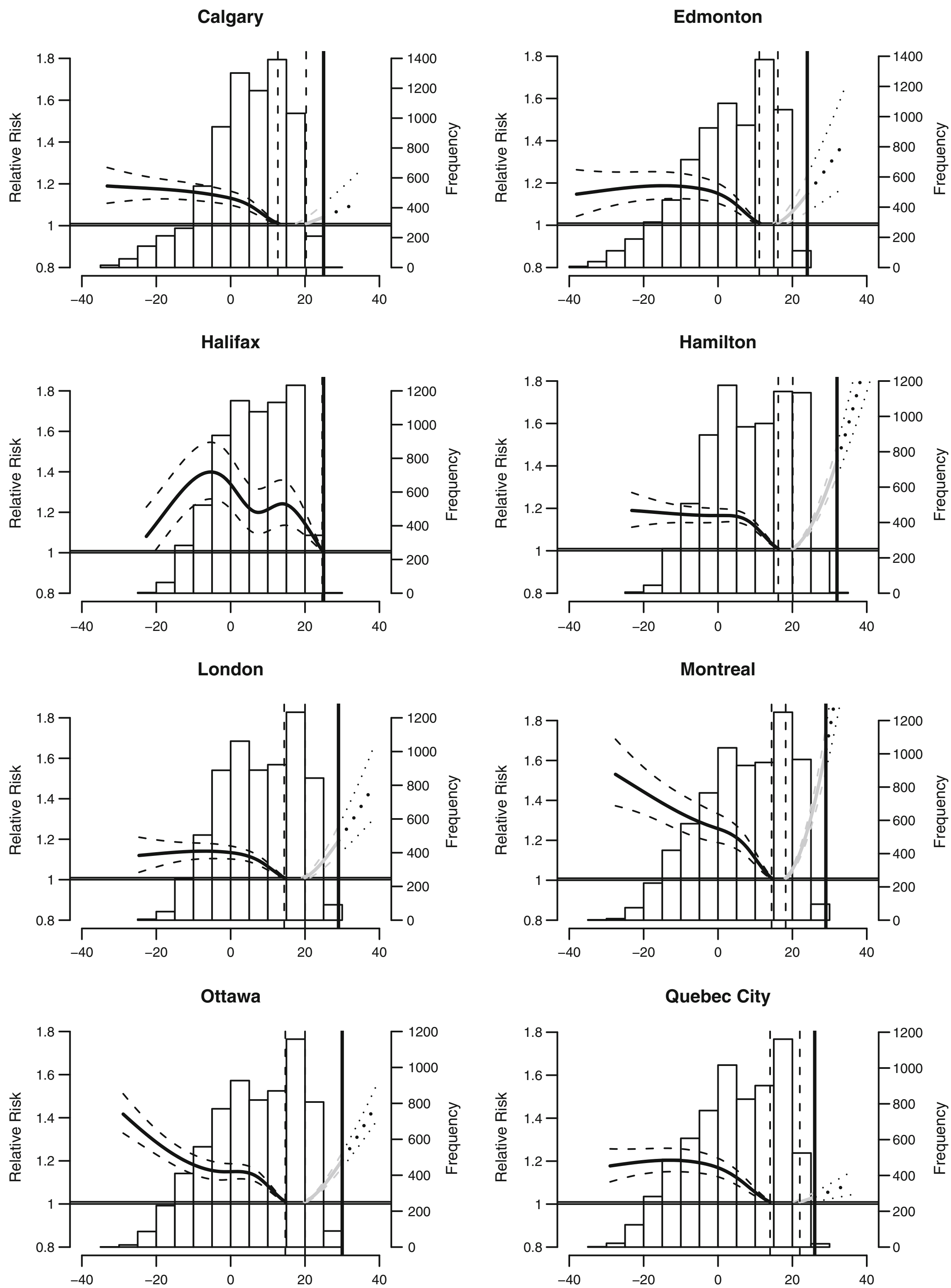

Fig. 2 City specific hot (*dark gray*) and cold temperature-mortality general linear models (*black*) incorporating lag and used to predict future mortality with extrapolation 10°C beyond the current maximum temperatures. The 95% confidence limits for each curve are indicated using *dashed lines*. Estimates where the confidence limits encompass 1.0 are considered not to be significantly different from 1.0. *Vertical dashed lines* indicate the upper and lower limits of the comfort zone. This information is superimposed on histograms of temperature frequency 1981–2000

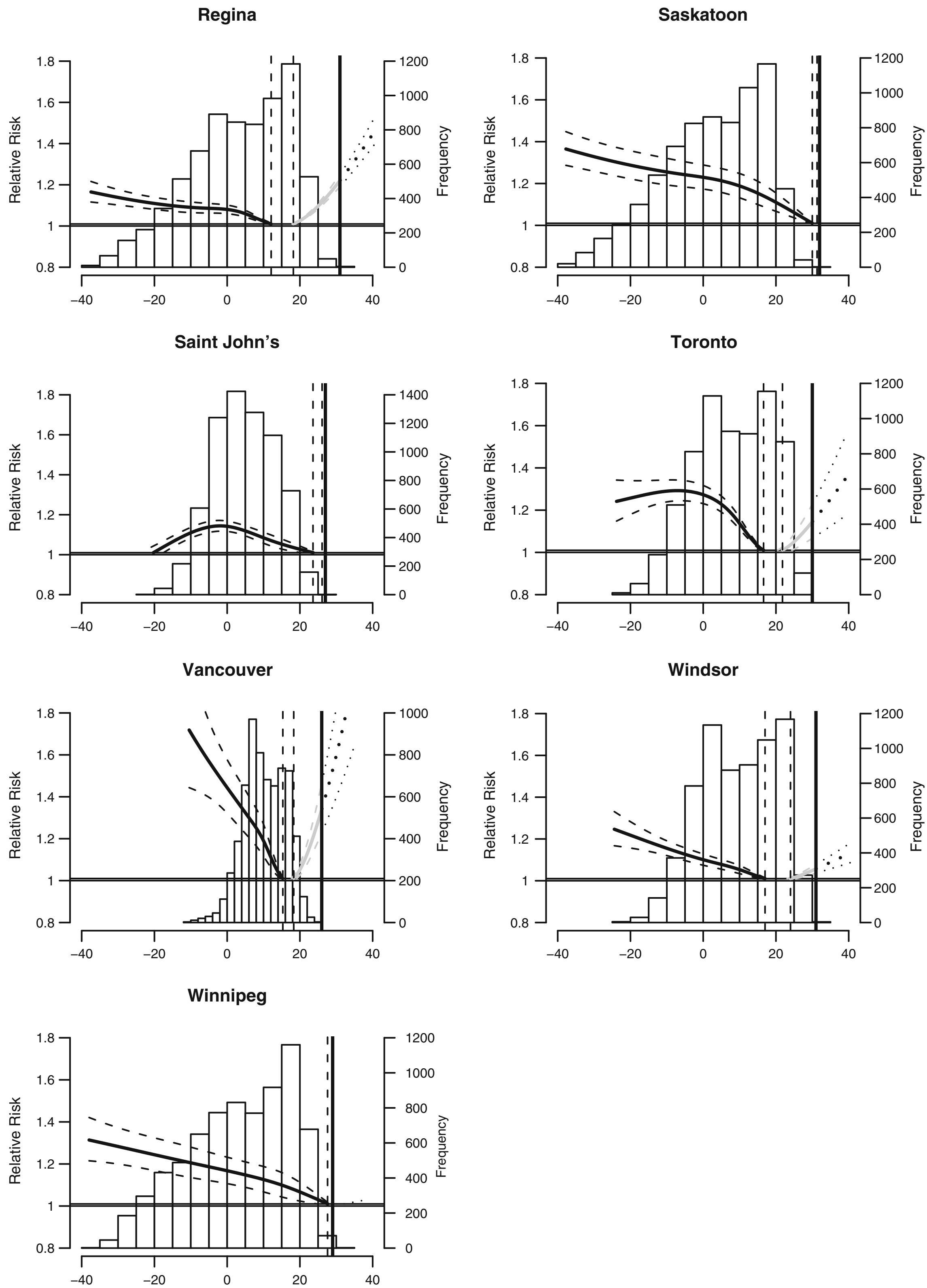

Fig. 2 (continued)

However, with the incorporation of lag, the cold tail of the relationship was steeper for Montreal and slightly flatter for London and Toronto. Additionally, the entire relationship for Vancouver became more U- than W-shaped.

The distributed lag models indicated that relative risk (RR) consistently dropped below 1.0 at approximately 1 week of lag for hot temperatures and between 2 and 3 weeks of lag for cold temperatures. This suggests some mortality displacement for both cold and hot temperatures. However, for hot temperatures this displacement seems to be greatest at the most extreme temperatures (99th percentile) and to quickly decrease in magnitude. As an example, in Toronto for temperatures corresponding to the 1st, 5th, and 10th percentiles, RR was highest at lag 0 and decreased as lag increased, crossing one between 17 and 20 days lag (Fig. 3a). As a result, the CRR (Fig. 3b) peaked between 17 and 20 days before decreasing. For the 90th, 95th and 99th percentile, RR was also highest at lag 0, but decreased sharply crossing 1.0 between 5 and 10 days lag (Fig. 3c) resulting in a peak in CRR between 5 and 7 days, and in CRR dropping below one between 15 and 20 days lag (Fig. 4c). While RR increased again at longer lags, this may be the result of examining too long a lag period for hot temperatures (Ballester et al. 1997). With few exceptions, the other cities showed similar relationships between the temperatures corresponding to these percentiles and mortality with differences primarily in the magnitude and significance of RR and CRR. The maximum and minimum CRR for selected temperatures along with the lag at which maximum and minimum CRR occurred are indicated in Supplementary Table 1.

With the exception of cities where the MMT occurred at the highest temperature experienced, the MMT generally fell between the 70th and 80th percentile of the temperature distribution for the city (Table 2). These MMTs would need to shift between 1.2°C in Saint John's and 3.9°C in Winnipeg for 2031–2050, between 1.9°C in Vancouver and 5.6°C in Halifax for 2051–2070 and between 3.2°C in Vancouver and 7.1°C in Winnipeg for 2071–2090 to maintain their current percentiles (data not shown). The lower limit of the MMT range typically fell between the 65th and 75th percentiles while the upper limit occurred at the 80th percentile or above (Table 2). The RR of mortality at the lowest temperatures was lower than the RR of mortality at current maximum temperatures in 10 of 15 cities, with average RRs of 1.26 and 1.15, respectively (Table 3). However, the 95% confidence intervals for RR at the minimum and maximum temperatures overlapped in 3 of the 10 cities. Four cities, Hamilton, London, Montreal, and Regina had greater RR

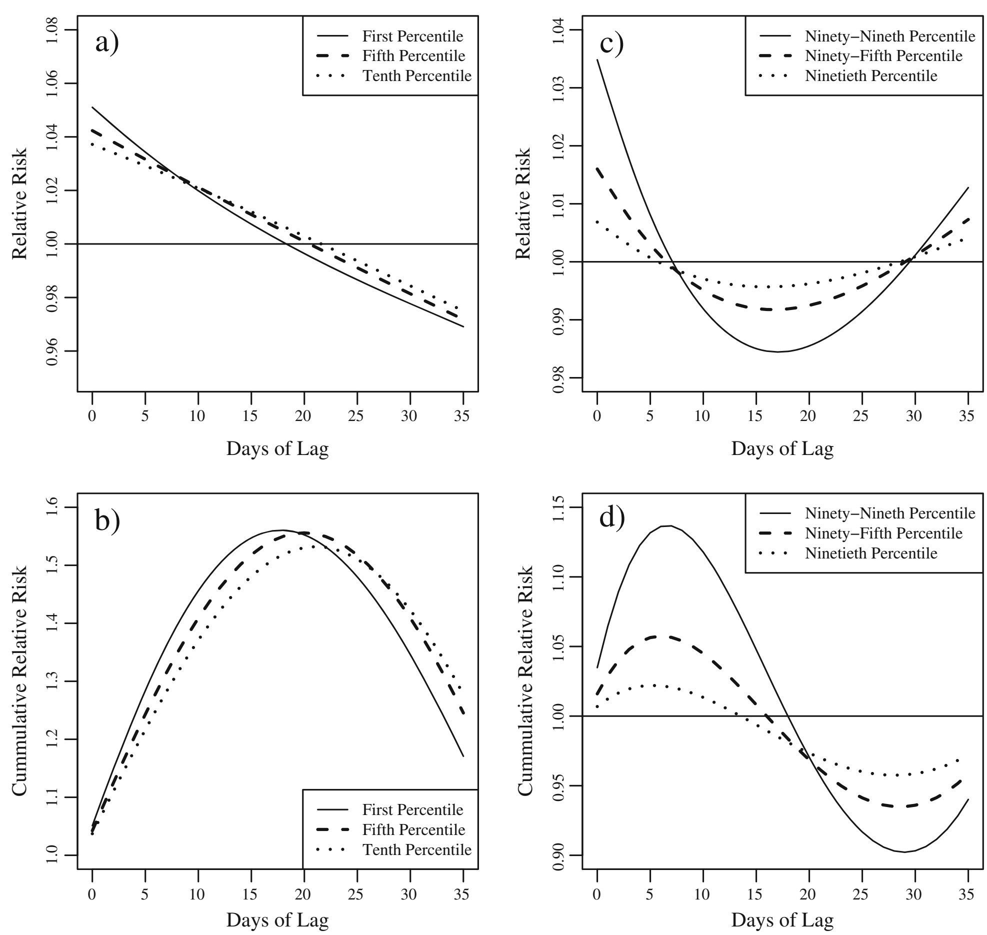

Fig. 3 Relative risk and cumulative relative risk over 35 days of lag for the city of Toronto. Relative risks above 1.0 indicate mortality rates are expected to be above those at the baseline, while relative risks below 1.0 indicate mortality is less than expected at the baseline. Confidence limits have been suppressed in these plots for clarity. Note that maximum y-axis values vary. **a** Relative risk across lag for the 1st, 5th, and 10th percentile of the temperature distribution indicating that greatest risk occurs at lag 0 and that relative risk drops below the baseline levels; **b** cumulative relative risk across lag at the 1st, 5th, and 10th percentile of temperatures indicating; **c** relative risk for 90th, 90th, and 99th percentile of the temperature distribution in Toronto; **d** relative risk for the 90th, 90th, and 99th percentile of the temperature distribution in Toronto

Table 2 Minimum mortality temperatures at zero days of lag, the number of days lag included in hot and cold general linear models, and the MMT range

	MMT[a] at lag 0	MMT percentile	Lag		MMT range[b]		Width	MMT range percentiles	
Calgary	14.8	82	6	6	12.7	20.3	7.6	73	99
Edmonton	12.8	75	9	9	11.1	17.5	6.4	69	93
Halifax	25.0	100	18	0	24.6	24.7	0.1	100	100
Hamilton	17.5	73	6	3	16.2	20.1	3.9	69	83
London	15.8	71	9	9	13.9	19.5	5.6	66	86
Montreal	15.2	70	12	3	14.4	18.5	4.1	67	81
Ottawa	15.8	73	6	0	14.6	20.9	6.3	69	91
Quebec City	15.7	78	6	0	13.7	22.0	8.3	73	98
Regina	15.0	76	3	0	12.1	18.2	6.1	68	87
Saskatoon	31.0	100	3	0	30.0	31.3	1.3	79	100
Saint John's	26.0	100	0	0	24.3	26.1	1.8	100	100
Toronto	18.1	80	3	3	17.2	22.7	5.5	74	95
Vancouver	16.0	80	15	3	15.3	18.3	3.0	76	92
Windsor	19.2	75	6	0	17.2	23.9	6.7	69	94
Winnipeg	29.0	100	6	0	14.2	28.9	14.7	100	100
Average	19.1	82.2	7.2	2.4	16.8	22.2	5.4	77	93

[a] Minimum mortality temperature in Celsius from distributed lag modeling at lag=0 using even year data only.

[b] Percentile of the minimum mortality temperature within the temperature distribution for each city

[c] Days of lag included in the "hot" and "cold" general linear models

[d] Minimum mortality temperature range or comfort zone corresponding to temperature with less than 1.01 relative risk of mortality compared to the MMT as estimated by the "hot" and "cold" general linear models using even year data

[e] Width of the MMT comfort zone in °C

[f] Percentiles corresponding to the upper and lower limits of the MMT

at the maximum temperatures during the base period when compared to the RR at the base period's minimum temperatures, while Saint John's RR was the same at the minimum and maximum temperatures. Only one city, Edmonton, was predicted to join this group if the maximum temperature increased by 4°C, and in this case the current RR at the minimum and maximum temperatures are estimated to be almost equal.

Temperature variation

We found no consistent trend in the standard deviation of maximum summer temperatures across the 56 cities we examined in Canada (Supplementary Table 2). In Ontario, three cities (Haliburton, London, and Welland), showed significant reductions in temperature variation over the time period examined. In contrast, three other cities Thunder Bay, Ontario; Mont Joli, Quebec; and St. Anthony, Newfoundland showed increases in temperature variation. However, six of seven significant trends in minimum winter temperature and nine of ten significant trends in average temperature showed decreased standard deviation. As a result, we chose not to alter temperature variation for the future periods.

Future temperature-related mortality

Temperatures were predicted to increase by an average of 1.7C, 2.9 and 4.4°C for 2031–2050, 2051–2070 and 2071–2090, respectively, across the 15 cities. However, the predictions for individual cities varied and winter temperatures were predicted to increase faster than summer temperatures. For each of the three future periods, city specific temperature anomalies for winter (December, January, and February; Table 4), and summer (June, July, and August; Table 5) are shown.

For all cities, the combination of removing secular variation with a natural spline of time and a factor for year and using a distributed lag model with a natural spline of average temperature, or using a general linear lag model with average temperature, was sufficient to reduce residuals to white noise. Neither the addition of potential confounders such as humidity, barometric pressure, day of the week or a factor indicating deaths from influenza nor the use of other temperature indicators resulted in significant improvements to the model. The 95% confidence intervals for the mortality estimated in odd years included the predictions made for the odd-year temperatures using the models constructed with even-year data, except for Ottawa where

Table 3 Relative risk at minimum and maximum temperatures with projected risk 2°C and 4°C above current maximum temperatures

City	Minimum temperature			Maximum temperature			Increase of 2°C			Increase of 4°C		
	Temp. °C	Relative risk[a]		Temp. °C	Relative risk		Temp. °C	Relative risk		Temp. °C	Relative risk	
Calgary	−33.19	1.19	(1.11–1.28)	24.80	1.04	(0.98–1.10)	26.80	1.05	(0.98–1.13)	28.80	1.07	(0.98–1.16)
Edmonton	−38.05	1.15	(1.04–1.26)	23.75	1.14	(1.06–1.23)	25.75	1.19	(1.08–1.30)	27.75	1.23	(1.11–1.38)
Halifax	−22.67	1.08	(0.95–1.23) [b]	24.68	1.00[c]	(1.00–1.00)						
Hamilton	−23.18	1.19	(1.11–1.27)	31.73	1.41	(1.34–1.48)	33.73	1.52	(1.43–1.61)	35.73	1.64	(1.52–1.76)
London	−24.63	1.12	(1.04–1.21)	28.34	1.17	(1.11–1.24)	30.34	1.23	(1.15–1.31)	32.34	1.28	(1.18–1.39)
Montreal	−27.57	1.53	(1.37–1.71)	28.18	1.57	(1.48–1.67)	30.18	1.77	(1.64–1.90)	32.18	1.98	(1.82–2.16)
Ottawa	−28.89	1.42	(1.33–1.51)	29.20	1.18	(1.15–1.21)	31.20	1.23	(1.19–1.27)	33.20	1.29	(1.24–1.34)
Quebec City	−29.01	1.18	(1.10–1.26)	25.75	1.03	(1.01–1.05)	27.75	1.04	(1.02–1.07)	29.75	1.06	(1.02–1.09)
Regina	−37.43	1.17	(1.12–1.22)	30.96	1.22	(1.19–1.25)	32.96	1.26	(1.23–1.30)	34.96	1.31	(1.27–1.36)
Saskatoon	−37.75	1.36	(1.29–1.45)	31.29	1.00 [c]	(1.00–1.00)						
Saint John's	−20.87	1.00	(0.97–1.04)	26.09	1.00 [c]	(1.00–1.00)						
Toronto	−23.82	1.24	(1.15–1.34)	29.43	1.13	(1.06–1.21)	31.43	1.17	(1.08–1.27)	33.43	1.22	(1.11–1.34)
Vancouver	−10.45	1.72	(1.44–2.05)	25.23	1.29	(1.19–1.40)	27.23	1.41	(1.27–1.56)	29.23	1.54	(1.36–1.74)
Windsor	−24.43	1.25	(1.17–1.33)	30.80	1.06	(1.04–1.08)	32.80	1.07	(1.05–1.10)	34.80	1.09	(1.06–1.12)
Winnipeg	−37.95	1.31	(1.22–1.42)	28.88	1.00 [c]	(1.00–1.00)						
Average [Range]	−27.99	1.26	(1.00–1.72)	27.94	1.15	(1.00–1.57)	29.94	1.19	(1.04–1.77)	31.94	1.24	(1.06–1.98)

[a] Risk relative to the risk at the minimum mortality temperature and 95% confidence limits

[b] Relative risk estimates with confidence intervals that encompass 1.0 are not considered statistically significant

[c] Maximum temperature corresponds to minimum mortality temperature and, therefore, risk is set to 1.00

Table 4 Predicted change in annual-cold related mortality rate per 100,000 population from the 1981–2000 base period

City	Base	2031–2050				2051–2070				2071–2090			
		Mortality predicted[a]		Δ[b]	Anom.[c]	Mortality predicted		Δ	Anom.	Mortality predicted		Δ	Anom.
Calgary	29.5	26.5	(24.9–28.1)	−3.1	2.4	25.3	(23.8–26.7)	−4.3	3.0	23.0	(21.4–24.6)	−6.8	3.9
Edmonton	33.9	31.3	(28.9–33.6)	−2.6	2.6	30.2	(28.1–32.2)	−3.7	3.3	28.1	(26.1–30.1)	−6.4	4.2
Halifax	135.7	126.7	(125.7–127.7)	−9.0	2.0	117.1	(114.2–120.0)	−18.6	3.8	109.6	(107.7–111.6)	−25.6	5.2
Hamilton	49.4	46.2	(43.8–48.6)	−3.2	2.5	42.3	(39.8–44.8)	−7.1	4.5	37.8	(35.1–40.5)	−11.7	6.4
London	47.8	42.5	(40.3–44.8)	−5.3	2.4	38.4	(36.5–40.3)	−9.4	4.3	33.4	(30.8–36.0)	−12.9	6.2
Montreal	38.3	34.3	(32.6–36.0)	−4.0	2.4	31.4	(29.9–32.9)	−6.9	4.5	28.0	(26.0–29.9)	−10.4	6.3
Ottawa	46.1	41.8	(40.1–43.5)	−4.3	2.4	38.9	(37.2–40.5)	−7.3	4.4	35.1	(33.0–37.1)	−11.1	6.1
Quebec City	46.3	42.1	(39.9–44.3)	−4.3	2.2	39.3	(37.3–41.3)	−7.1	4.4	35.8	(33.6–38.1)	−9.8	6.1
Regina	39.4	36.7	(32.9–40.5)	−2.7	1.9	34.7	(31.2–38.2)	−4.7	3.1	32.4	(28.8–36.1)	−7.0	4.1
Saskatoon	132.4	126.9	(126.4–127.5)	−5.5	1.9	123.4	(122.8–123.9)	−9.0	3.1	117.3	(116.6–118.0)	−15.2	4.0
Saint John's	61.5	59.6	(59.1–60.0)	−1.9	1.0	58.2	(57.4–59.0)	−3.2	2.1	55.5	(54.9–56.1)	−6.0	3.6
Toronto	34.5	31.2	(30.0–32.5)	−3.3	2.5	28.0	(26.9–29.2)	−6.5	4.4	24.7	(23.4–26.0)	−9.1	6.2
Vancouver	52.0	38.7	(36.5–40.9)	−13.3	2.4	37.7	(34.9–40.4)	−14.4	2.8	30.3	(28.3–32.4)	−22.8	4.1
Windsor	46.8	39.6	(36.2–43.0)	−7.3	2.6	34.2	(30.6–37.9)	−12.6	4.4	29.6	(26.1–33.1)	−16.0	6.2
Winnipeg	83.7	78.8	(78.3–79.3)	−5.0	2.4	74.8	(74.4–75.3)	−8.9	4.1	69.5	(69.0–70.1)	−14.3	5.3
Average [Range]	58.5	53.5	(26.5–126.9)	−5.0	2.2	50.3	(25.3–123.4)	−8.2	3.7	46.0	(23.0–117.3)	−12.5	5.2

[a] Mortality predicted using city specific cold general linear models and future temperature series

[b] Change in mortality rate from base period

[c] Winter (December, January and February) temperature anomaly compared to base period (1981–2000) in °C

Table 5 Predicted change in annual heat-related mortality rate per 100,000 population from the 1981–2000 base period

City	Base	2031–2050				2051–2070				2071–2090			
		Mortality predicted[a]		Δ[b]	Anom.[c]	Mortality predicted		Δ	Anom.	Mortality predicted		Δ	Anom.
Calgary	−0.05[d]	0.04	(−0.27−0.35) [d]	0.09	1.6	0.18	(−0.13−0.49)	0.23	2.7	0.58	(0.25−0.91)	0.63	4.7
Edmonton	1.36	2.52	(1.21−3.83)	1.16	1.5	3.43	(2.14−4.72)	2.07	2.5	5.92	(4.61−7.23)	4.56	4.3
Halifax	0.00				1.5				2.8				4.0
Hamilton	4.36	11.55	(8.96−14.14)	7.19	2.2	19.50	(16.97−22.03)	15.14	3.9	29.53	(26.75−32.31)	25.17	5.8
London	4.25	9.27	(6.39−12.15)	5.02	2.2	15.27	(12.27−18.27)	11.02	3.9	23.03	(19.74−26.32)	18.78	5.8
Montreal	5.02	10.26	(8.69−11.83)	5.24	1.8	16.96	(14.92−19.00)	11.94	3.4	23.28	(20.59−25.97)	18.26	4.9
Ottawa	0.86	3.71	(2.30−5.12)	2.85	1.9	7.07	(5.70−8.44)	6.21	3.4	10.59	(9.04−12.14)	9.73	5.0
Quebec City	0.16	0.57	(−0.16−1.30)	0.41	1.6	1.10	(0.36−1.84)	0.94	3.0	1.70	(1.01−2.39)	1.54	4.4
Regina	2.77	6.00	(3.10−8.90)	3.23	1.7	8.88	(5.76−12.00)	6.11	3.2	14.89	(11.66−18.12)	12.12	5.4
Saskatoon	0.00				1.5				2.7				4.9
Saint John's	0.00				0.9				1.6				2.9
Toronto	0.41	1.41	(0.84−1.98)	1.00	2.1	2.66	(2.03−3.29)	2.25	3.8	4.17	(3.52−4.82)	3.76	5.5
Vancouver	0.53	2.25	(1.21−3.29)	1.72	1.7	3.51	(2.51−4.51)	2.98	2.4	6.71	(5.63−7.79)	6.18	3.8
Windsor	0.90	2.57	(1.04−4.10)	1.67	2.1	4.56	(3.13−5.99)	3.66	3.7	6.82	(5.41−8.23)	5.92	5.2
Winnipeg	0.00				1.7				3.1				5.6
Average	1.37	3.34	(0.04−11.55)	1.97	1.7	5.54	(0.18−19.50)	4.17	3.1	8.48	(0.58−29.53)	7.11	4.8

[a] Mortality predicted using city specific hot general linear models and future temperature series

[b] Change in mortality rate from base period

[c] Summer (June, July and August) temperature anomaly compared to base period (1981–2000) in °C

[d] As discussed in the methods, since there are both positive excess mortalities and negative mortality deficits following subtraction of the baseline mortality rate negative mortality rates can occur for the base period. The 95% confidence interval (not shown) indicates the estimate is not significantly different from zero

the predicted heat-related mortality was greater than the estimated observed value, and for Hamilton where the predicted cold-related mortality was greater than the estimated value (Supplementary Table 3). However, in both cases, the 95% confidence intervals overlapped. Changes to the model for removing secular variation caused minor alteration to estimates, as did changing the mortality model (Supplementary Tables 1 and 5). However, increasing the number of degrees of freedom in the spline for time from 15 to 20 *df*/year dramatically reduced the mortality associated with cold temperatures and alone was able to reduce the residuals to white noise in many cases. Similarly, incorporating 21 days of lag in all mortality models reduced both the baseline and predicted heat-related mortality.

Annual excess mortality estimated to be the result of cold temperatures during 1981–2000 (Table 4) were greater than the annual excess heat-related mortality in all cases (Table 5). Current annual cold-related excess mortality averaged 58.5 (range 29.5–135.7) deaths per 100,000 across all cities, while annual heat-related excess mortality averaged 1.4 (range −0.05 to 5.02) deaths per 100,000. As expected, increased temperatures are predicted to reduce cold-related mortality and to increase heat-related mortality in the majority of cities (Tables 4 and 5). Four cities, Hamilton, London, Montreal, and Regina, are predicted to show increased burdens of heat-related mortality that will not be offset by decreased cold-related mortality. Of these, Hamilton is predicted to see the largest additional burden, with increases of 7, 15 and 25% for 2031–2050, 2051–2070 and 2071–2090, respectively, compared to current mortality burdens. Given the bias noted in Hamilton's model of cold-related mortality, these estimates are likely conservative. Regina is predicted to show the smallest increase of 1, 3, and 12%. The other 11 cities are expected to show reduced temperature-related mortality burdens. For example, Vancouver is expected to show the greatest reduction with decreases of 24, 24 and 32 for 2031–2050, 2051–2070 and 2071–2090, respectively.

Discussion

Many health outcomes including death from cardiovascular and respiratory illnesses are associated with exacerbation of underlying conditions by exposure to cold or hot temperatures (Havenith 2005; Näyäh 2005). With temperatures increasing as a result of global warming, it is important to address the uncertainty surrounding the impact of higher temperatures by examining both potential reductions in cold-related mortality and potential increases in heat-related mortality.

Current temperature–mortality relationships in most of the Canadian cities examined here are J-, W- or U-shaped, with a minimum mortality temperature (MMT) and comfort zone at the warmer end of the temperature range. The shape of the temperature–mortality relationships and the lagged effects of temperature found in this study are concordant with those observed by other researchers (Kunst et al. 1993; Keatinge et al. 2000; Schwartz 2000; Braga et al. 2001; Laaidi et al. 2006). For example, the MMT ranges we identified are similar to those estimated for other northern and temperate countries (Keatinge et al. 2000; Curriero et al. 2002; Donaldson et al. 2001, 2003; Laaidi et al. 2006). Other researchers have also found similar lag structures with short-term effects for hot temperatures and long-term effects for cold temperatures (Ballester et al. 1997; Huynen et al. 2001; Díaz et al. 2005). Additionally, and as in previous work, we found that cities located close together often have roughly similar temperature–mortality relationships (Ballester et al. 1997). For example, the temperature–mortality relationship in both Halifax and Saint John's indicates that the lowest mortality rates correspond to the highest temperature experienced, and that there is a positive relationship between the coldest temperatures and mortality. Similarly, cities located in the prairies (Calgary, Edmonton, Regina, Saskatoon, and Winnipeg) show a relatively flat or shallow negative mortality–temperature relationship below the MMT, resulting in a linear relationship or a J-shape. In contrast, most cities in southern Ontario and Quebec show a curve that is closer to a U-shape with a flat tail at colder temperatures. However, Ottawa and Montreal show a steep cold tail. Previous work has suggested that differences among cities result from differences in socio-economic status, the age of the population and meteorological variation typical for the location (Healy 2003; Davis et al. 2003; Laaidi et al. 2006; Kinney et al. 2008). This last factor may explain the tendency for cities in the same geographic area to have similar temperature–mortality relationships. We do not, however, have enough spatial coverage given the number of large cities across the large area represented by Canada to perform a detailed analysis of spatial patterns comparable to that undertaken by others in the U.S.A. (i.e., Kalkstein and Greene 1997).

It has been suggested that the highly anomalous 2003 European heat wave could indicate a shift toward a more variable temperature regime (Meehl and Tebaldi 2004; Schär et al. 2004). This is a concern, as increased variability would have a greater effect on the number of days with extreme temperatures than would a shift in the mean temperature (Katz and Brown 1992). However, like previous researchers (Easterling et al. 1997; Bonsal et al. 2001; Peterson et al. 2008), we see no evidence that temperature variation has increased over the past century based on analysis of homogenized temperature series (Vincent et al. 2002). As a result, although temperature variability may change in the future, based on the historical record for Canada we cannot estimate an appropriate increase in variability to apply to future temperature series.

For most cities included here, the increased heat-related mortality was balanced by decreased cold-related mortality, which remains the cause of the majority of temperature-related deaths. However, there are four exceptions to this prediction: Hamilton, London, Montreal, and Regina. For these cities, the RR estimated at the current maximum temperatures is greater than the RR at the current minimum temperature. This contributes to an overall increase in risk with warmer temperatures. Overall, in comparison to current heat-related mortality rates, the percentage increases in heat-related mortality are large, nearly tripling by 2021–2040, increasing by nearly five-fold by 2051–2070 and by more than eight-fold by 2081–2100. This is comparable to the prediction of doubled heat-related mortality by 2050 for Montreal, Ottawa, Toronto, and Windsor by Cheng et al. (2005), and by Duncan et al.'s (1997) estimates of 5- to 20-fold increases for Montreal, Ottawa, and Toronto, for a doubling of atmospheric carbon dioxide. However, in terms of magnitude, the change in heat-related mortality is usually small compared to the change in cold-related mortality. For example, for Vancouver in 2031–2050, the annual cold-related mortality rate is predicted to decrease by 13.3/100,000, a 26% decline from the base period level of 52.0/100,000, while heat-related mortality is predicted to rise by 1.72/100,000, an increase of 325% from the baseline of 0.53/100,000. This is in line with Keatinge et al.'s (2000) estimate that, for seven European cities, the average cold-related mortality burden was 200.3 per 100,000 while heat-related mortality was 21.7 per 100,000, concluding that moderate amounts of warming were likely to result in an overall decrease in temperature-related mortality. In contrast, Kalkstein and Greene (1997) estimated that by 2050 climate change would result in a large increase of 1,300–3,000 heat-related deaths in 44 large U.S. cities, but only slight decreases of between 100 and 200 cold-related deaths. Similarly, Doyon et al. (2008) concluded that Quebec City, Montreal, and Saguenay would experience increased burdens of temperature-related mortality for 2020, 2050 or 2080 under either the A2 or B2 scenarios. Interestingly, we draw a similar conclusion for Montreal, though we predict a decrease in temperature-related mortality for Quebec City.

As with all predictions of future conditions, the mortality estimates presented here have numerous sources of uncertainty (reviewed by Stott and Kettleborough 2002; Gosling et al. 2009b). Indeed, Doyon et al. (2008) suggested that estimates of future mortality are only starting points for estimating the order of magnitude of temperature-related deaths from climate change. Some of these sources are intrinsic to ecological studies, such as using outside temperature as a measure of exposure and excluding potential confounders (Gosling et al. 2009b). However, there are two additional sources of uncertainty that warrant consideration.

The first source of uncertainty is the assumption that current temperature–mortality relationships are representative of future temperature–mortality relationships. Given that temperature–mortality relationships are linked to biological and socio-economic factors, and that populations have the ability to acclimatize to increased temperatures through both behavioral and technological means, they can change over time (Keatinge et al. 2000; Davis et al. 2003; Dessai 2002, 2003; Carson et al. 2006; Kinney et al. 2008; Gosling et al. 2009b). Shifts in the MMT temperatures averaging 0.5°C per decade would be needed to maintain the current percentile position of the MMTs across the three future periods. Additionally, if the pool of susceptible individuals is shared for hot- and cold-mortality, decreased cold-related mortality may result in a greater pool of individuals susceptible to heat-related mortality. This would result in a greater shift toward heat-related mortality than predicted here (Rocklöv and Forsberg 2009; Stafoggia et al. 2009). However, given that there is currently no way to predict how temperature–mortality relationships will change in future, the current temperature–mortality relationship is likely our best source of information at this time.

The second source of uncertainty is the predicted future temperatures. Climate models have become increasingly sophisticated, but uncertainties still arise from an imperfect understanding of the Earth's climate system and unknown parameters such as future greenhouse gas emissions (Meehl et al. 2007; Lenton et al. 2008). Estimating future temperatures using multiple models and for more than one scenario is a common way to deal with this uncertainty, but high-resolution dynamically downscaled future temperature predictions are currently available only for the A2 scenario for Canada. However, since climate models show similar results—regardless of emission scenario—for the mid- to late century, the near-term estimates of temperature and resulting mortality changes may be relatively insensitive to changes in emission scenario (Meehl et al. 2007). Furthermore, the results presented here predict the outcome of temperature shifts ranging over an average of 0.9–4.4°C, even if these changes occur earlier than predicted in the A2 projection used in this paper.

This study could be extended by examining the temperature–mortality relationships for higher-risk populations such as the elderly, and stratifying mortality by cause, as respiratory and cardiovascular disease have different associations with temperature (Smoyer et al. 2000; Basu and Samet 2002; Braga et al. 2002; Curriero et al. 2002; Laaidi et al. 2006). Additionally, air pollution data are not available for all the cities here and neither were projections of future air pollution levels, but air pollution may have a significant role in temperature-related mortality (Gosling et al. 2009a). Furthermore, incorporating temperature projections from additional scenarios would be valuable for quantifying the uncertainty in the estimates of future temperature-related mortality resulting from uncertainty in the magnitude and timing of future temperature change. Each of these issues warrant future examination, but are beyond the scope of the current paper.

In conclusion, temperature increases for Canada given the A2 scenario are expected to result in a decreased cold-related mortality burden and an increased heat-related mortality burden, but the balance of these changes varies among cities. Specifically, increased burdens are predicted in Hamilton, London, Montreal, and Regina and decreased burdens are predicted in the other 11 cities (Calgary, Edmonton, Halifax, Ottawa, Quebec City, Saskatoon, Saint John's, Toronto, Vancouver, Winnipeg, and Windsor). Additionally, for Canadian cities, we find no evidence that there has been a consistent trend toward increased temperature variation. However, these predictions should not diminish efforts to mitigate temperature stress, as the ultimate burden of hot and cold temperature-related mortality will depend on societal decisions regarding issues spanning urban design and investment in health care (Klinenberg 2002; Davis et al. 2003; Hayhoe et al. 2004; Donaldson and Keatinge 2008).

Acknowledgements We thank Richard Fortin from Statistics Canada for his kind help interpreting census data, Lucie Vincent for providing homogenized temperature series data, reviewers at Health Canada, and anonymous reviewers for their suggestions for improving the manuscript.

References

Akaike H (1973) Information theory and extension of the maximum likelihood principle. In: Petrov BN, Csaki F (eds) Second International Symposium on Information Theory. Akademiai Kiado, Budapest, pp 267–281

Armstrong B (2006) Models for the relationship between ambient temperature and daily mortality. Epidemiology 17(6):624–6131

Baer H, Singer M (2009) Global Warming and the Political Ecology of Health. Left Coast Press, California, USA

Ballester F, Corell D, Pérez-Hoyos SM, Hervás A (1997) Mortality as a function of temperature. A study in Valencia, Spain, 1991–1993. Int J Epidemiol 23(3):551–561

Barnett AG, Tong S, Clements ACA (2010) What measure of temperature is the best predictor of mortality? Environ Res 110 (6):604–611

Basu R, Samet JM (2002) Relation between ambient temperature and mortality: a review of the epidemiologic evidence. Epidemiol Rev 24(2):190–202

Bonsal BR, Zhang X, Vincent LA, Hogg WD (2001) Characteristics of daily temperature over Canada. J Climate 14:1959–1976

Braga ALF, Zanobetti A, Schwartz J (2001) The time course of weather-related deaths. Epidemiology 12(6):662–667

Braga ALF, Zanobetti A, Schwartz J (2002) The effects of weather on respiratory and cardiovascular deaths in 12 U.S. cities. Environ Health Perspect 110(9):859–863

Bull GM, Morton J (1978) Environment, temperature and death rates. Age Ageing 7(4):210–224

Campbell-Lendrum DH, Corvalán CF, Prüss-Ustün A (2003) How much disease could climate change cause? In: McMicheal AJ, Campbell-Lendrum DH, Corvalán CF, Ebi KL, Githeko AK, Scheraga JD, Woodword A (eds) Climate change and human health risk and responses. World Health Organization, Geneva, pp 133–155

Carson C, Hajat S, Armstrong B, Wilkinson P (2006) Declining vulnerability to temperature-related mortality in London over the 20th century. Am J Epidemiol 164(1):77–84

Cheng CS, Campbell M, Li Q, Li G, Auld H, Day N et al (2005) Differential and combined impacts of winter and summer weather and air pollution due to global warming on human mortality in south-central Canada. Technical report. Health Canada, Ottawa, Canada

Costello A, Mustafa A, Allen A, Ball S, Bell S, Bellamy R et al (2009) Managing the health effects of climate change. Lancet 373:1698–1733

Curriero FC, Heiner KS, Samet JM, Zeger SL, Strug L, Patz JA (2002) Temperature and mortality in 11 cities of the eastern Unites States. Am J Epidemiol 155(1):80–87

Davis RE, Knappenberger PC, Michaels PJ, Novicoff WM (2003) Changing heat-related mortality in the United States. Environ Health Perspect 111(14):1712–1718

Davis RE, Knappenberger PC, Michaels PJ, Novicoff WM (2004) Seasonality of climate-human mortality relationships in US cities and impacts of climate change. Clim Res 26:61–76

Déqué M (2007) Frequency of precipitation and temperature extremes over France in an anthropogenic scenario: model results and statistical correction according to observed values. Glob Planet Change 57:16–26

Dessai S (2002) Heat stress and mortality in Lisbon Part I. Model construction and validation. Int J Biometeorol 47:6–12

Dessai S (2003) Heat stress and mortality in Lisbon Part II. An assessment of the potential impacts of climate change. Int J Biometeorol 48:37–44

Díaz J, García R, López C, Linares C, Tobías A, Prieto L (2005) Mortality impact of extreme winter temperature. Int J Biometerol 49:179–183

Donaldson G, Keatinge W (2008) Direct effects of rising temperatures on mortality in the UK. In: Kovats S (ed) Health Effects of Climate Change in the UK – 2008 update. Department of Health, UK, pp 81–89

Donaldson G, Kovats RS, Keatinge WR, McMichael AJ (2001) 4.1 Heat- and cold-related mortality and morbidity and climate change, Health effects of climate change in the UK. Department of Health, UK

Donaldson GC, Keatinge WR, Näyhä S (2003) Changes in summer temperature and heat-related mortality since 1971 in North Carolina, South Finland and Southeast England. Environ Res 91:1–7

Doyon B, Bélanger D, Gosselin P (2008) The potential impact of climate change on annual and seasonal mortality for three cities in Québec, Canada. Int J Health Geogr 7:23–35

Duncan K, Guidotti T, Cheng W, Naidoo K, Gibson G, Kalkstein L, Sheridan S, Waltner-Towes D, MacEachern S, Last J (1997) Health Sector, Canada country study: impacts and acclimatization. Environment Canada, Canada, pp 520–532

Easterling DR, Horton B, Jones PJ, Peterson TC, Karl TR, Parker DE, Salinger MJ, Razuvayev V, Plummer N, Jamason P, Folland CK (1997) Maximum and minimum temperature trends for the globe. Science 277(5324):364–367

Epstein PR (2005) Climate change and human health. N Engl J Med 353(14):1433–1436

Eurowinter Group (1997) Cold exposure and winter mortality from ischaemic heart disease, cerebrovascular disease, respiratory disease, and all causes in warm and cold regions of Europe. Lancet 349:1341–1346

Gasparrini A, Armstrong B (2010) Time series on the health effects of temperature: Advancements and limitations. Environ Res 110:633–638

Gasparrini A, Armstrong B (2011) The impact of heat waves on mortality. Epidemiology 22:68–73

Gosling SN, Lowe JA, McGregor GR, Pelling M, Malamud BD (2009a) Associations between elevated atmospheric temperature and human mortality: a critical review of the literature. Clim Change 92:299–341

Gosling SN, McGregor GR, Lowe JA (2009b) Climate change and heat-related mortality in six cities Part 2: climate model evaluation and projected impacts from changes in the mean and variability of temperature with climate change. Int J Biometeorol 53:31–51

Guest CS, Wilson K, Woodward AJ, Hennessy K, Kalkstein LS, Skinner C, McMicheal AJ (1999) Climate and mortality in Australia: retrospective study, 1979–1990, and predicted impacts in five major cities in 2030. Clim Res 13:1–15

Hajat S, Armstrong B, Baccini M, Biggeri A, Bisanti L, Russo A, Paldy A, Menne B, Kosatsky T (2006) Impact of high temperature on mortality. Is there an added heat wave effect? Epidemiology 17:632–638

Hassi J (2005) Cold extremes and impacts on health. In: Kirch W, Menne B, Bertollini R (eds) Extreme weather events and public health responses. Springer, Berlin, pp 59–67

Havenith G (2005) Temperature regulation, heat balance and climatic stress. In: Kirch W, Menne B, Bertollini R (eds) Extreme weather events and public health responses. Springer, Berlin, pp 79–80

Hayhoe K, Cayan D, Field CB, Frumhoff PC, Maurer EP, Miller NL et al (2004) Emissions pathways, climate change and impacts on California. Proc Natl Acad Sci USA 101(34):12422–12427

Healy JD (2003) Excess winter mortality in Europe: a cross country analysis identifying key risk factors. J Epidemiol Community Health 57:784–789

Huynen MM, Martens P, Schram D, Weijenberg MP, Kunst AE (2001) The impact of heat waves and cold spells on mortality rates in the Dutch population. Environ Health Perspect 109(5):463–470

Kalkstein LS, Greene JS (1997) An evaluation of climate/mortality relationships in large U.S. cities and the possible impacts of climate change. Environ Health Perspect 105(1):84–93

Katz RW, Brown BG (1992) Extreme events in a changing climate: variability is more important than averages. Climate Change 21:289–302

Keatinge WR, Donaldson GC (2004) The impact of global warming on health and mortality. South Med J 97(11):1093–1099

Keatinge WR, Donaldson GC, Cordioli E, Martinelle M, Kunst AE, Mackenbach JP, Nayha S, Vuori I (2000) Heat related mortality in warm and cold regions of Europe: observational study. BMJ 321:670–673

Kinney PL, O'Neill MS, Bell ML, Schwartz J (2008) Approaches for estimating effect of climate change on heat-related deaths: challenges and opportunities. Environ Sci Policy 11:87–96

Klinenberg E (2002) Heat wave: a social autopsy of disaster in Chicago. University of Chicago Press, Chicago

Knowlton K, Lynn B, Goldberg RA, Rosenweig C, Rosenthal JK, Kinney PL (2007) Projecting heat-related mortality impacts under a changing climate in the New York City Region. Am J Public Health 97(11):2028–2034

Kolb S, Radon K, Valois M-F, Heguy L, Goldberg MS (2007) The short-term influence of weather on daily mortality in congestive heart failure. Arch Environ Occup Health 62(4):169–176

Kovats RS, Hajat S (2008) Heat stress and public health: A critical review. Annu Rev Public Health 29:41–55

Kunst AE, Looman CWN, Mackenbach JP (1993) Outdoor air temperature and mortality in the Netherlands: A time series analysis. Am J Epidemiol 137(3):331–341

Laaidi M, Laaidi K, Besancenot J-P (2006) Temperature-related mortality in France, a comparison between regions with different climates from the perspective of global warming. Int J Biometeorol 51:145–153

Langford IH, Bentham G (1995) The potential effects of climate change on winter mortality in England and Wales. Int J Biometeorol 38:141–147

Le Terte A, Lefranc A, Eilstein D, Declercq C, Medina S, Blanchard M et al (2006) Impact of the 2003 heatwave on all-cause mortality in 9 French cities. Epidemiology 17:75–79

Lemmen DS, Warren FJ (eds) (2004) Chapter 9: Human health and well-being, Climate Change Impacts and Acclimatization: A Canadian Perspective Climate change impacts and acclimatization. Directorate NRCan, Ottawa, Canada, pp 151–169

Lenton TM, Held H, Kreigler E, Hall JW, Lucht W, Rahmstorf S, Schellnhuber HJ (2008) Tipping elements in the Earth's climate system. Proc Natl Acad Sci USA 105(6):1786–1793

Martens WJM (1998) Climate change, thermal stress and mortality changes. Soc Sci Med 46(3):331–344

McMichael AJ (1993) Global environmental change and human population health: a conceptual and scientific challenge for epidemiology. Int J Epidemiol 22(1):1–8

McMichael AJ, Woodruff RE, Hales S (2006) Climate change and human health: present and future risks. Lancet 367:859–869

Medina-Ramón M, Schwartz J (2007) Temperature, temperature extremes, and mortality: a study of acclimatization and effect modification in 50 US cities. Occup Environ Med 64:827–833

Meehl GA, Tebaldi C (2004) More intense, more frequent, and longer lasting heat waves in the 21st century. Nature 305:994

Meehl GA, Zwiers F, Evans J, Knutson T, Mearns L, Whetton P (2001) Trends in extreme weather and climate events: issues related to modeling extremes in projections of future climate change. Bull Am Meteorol Soc 81(3):427–436

Meehl GA, Collins WD, Friedlingstein P, Gaye AT, Gregory JM, Kitoh A et al (2007) Global climate change projections. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate Change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the International Panel on Climate Change. Cambridge University Press, Cambridge, pp 748–845

Mercer JB (2003) Cold – an underrated risk factor for health. Environ Res 92:8–12

Music B, Caya D (2007) Evaluation of the hydrological cycle over the Mississippi river basin as simulated by the Canadian Regional Climate Model (CRCM). J Hydrometeorol 8(5):969–988

Nakićenović N, Swart R (eds) (2000) Special report on emission scenarios. Cambridge University Press, Cambridge

Näyäh S (2005) Environmental temperature and mortality. Int J Circumpolar Health 64:5

Peterson TC, Zhang X, Brunet-India M, Vazque-Aguirre JL (2008) Changes in North American extremes derived from daily weather data. Journal of Geophysical Research 113: doi:10.1029/2007JD009453

Pielke R, Wigley T, Green C (2008) Dangerous assumptions. Nature 452(3):531–532

Robine J-M, Cheung SLK, Le Roy S, Oyen HV, Griffiths C, Michel J-P, Herrmann FR (2008) Death toll exceeded 70,000 in Europe during the summer of 2003. C.R. Biol 331:171–178

Rocklöv J, Forsberg MK (2009) Winter mortality modifies the heat-mortality association the following summer. Eur Respir J 33:245–251

Schär C, Vidale PL, Lüthi D, Frei C, Häberll C, Liniger MA, Appenzeller C (2004) The role of increasing temperature variability in European summer heatwaves. Nature 427:332–336

Schneider S (2009) The worst-case scenario. Nature 458(30):1104–1105

Schwartz J (2000) The distributed lag between air pollution and daily deaths. Epidemiology 11(3):320–326

Scinocca JF, McFarlane NA (2004) The Variability of Modelled Tropical Precipitation. J Atmos Sci 61:1993–2015

Smoyer KE, Rainham DCG, Hewko JN (2000) Heat-stress-related mortality in five cities in Southern Ontario: 1980–1996. Int J Biometeorol 44:190–197

Stafoggia M, Forastiere F, Michelozzi P, Perucci CA (2009) Summer temperature-related mortality: effect modification by previous winter mortality. Epidemiology 20:575–583

Stott PA, Kettleborough JA (2002) Origins and estimates of uncertainty in predictions of twenty-first century temperature rise. Nature 416:723–726

Vincent LA, Zhang X, Bonsal BR, Hogg WD (2002) Homogenization of daily temperatures over Canada. J Climate 15:1322–1334

Weaver AJ (2004) The Science of Climate Change. In: Coward H, Weaver AJ (eds) Hard choices climate change in Canada. Wilfred Laurier University Press, Waterloo, Canada, pp 13–14

World Health Organization (WHO). 2007. International Classification of Diseases, 10th Revision (ICD-10). Available: http://www.who.int/classifications/icd/en/ [accessed 28 April 2011]