

Differential and combined impacts of extreme temperatures and air pollution on human mortality in south–central Canada. Part II: future estimates

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Received: 30 June 2008 / Accepted: 23 January 2009 / Published online: 18 February 2009
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Abstract This paper forms the second part of an introduction to a synoptic weather typing approach to assess differential and combined impacts of extreme temperatures and air pollution on human mortality, focusing on future estimates. A statistical downscaling approach was used to downscale daily five general circulation model (GCM) outputs (three Canadian and two US GCMs) and to derive six-hourly future climate information for the selected cities (Montreal, Ottawa, Toronto, and Windsor) in south–central Canada. Discriminant function analysis was then used to project the future weather types, based on

historical analysis defined in a companion paper (Part I). Future air pollution concentrations were estimated using the within-weather-type historical simulation models applied to the downscaled future GCM climate data. Two independent approaches, based on (1) comparing future and historical frequencies of the weather groups and (2) applying within-weather-group elevated mortality prediction models, were used to assess climate change impacts on elevated mortality for two time windows (2040–2059 and 2070–2089). Averaging the five GCM scenarios, across the study area, heat-related mortality is projected to be more than double by the 2050s and triple by the 2080s from the current condition. Cold-related mortality could decrease by about 45–60% and 60–70% by the 2050s and the 2080s, respectively. Air pollution-related mortality could increase about 20–30% by the 2050s and 30–45% by the 2080s, due to increased air pollution levels projected with climate change. The increase in air pollution-related mortality would be largely driven by increases in ozone effects. The population acclimatization to increased heat was also assessed in this paper, which could reduce future heat-related mortality by 40%. It is most likely that the estimate of future extreme temperature- and air pollution-related mortality from this study could represent a bottom-line figure since many of the factors (e.g., population growth, age structure changes, and adaptation measures) were not directly taken into account in the analyses.

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Keywords Synoptic weather typing ·
Climate change scenarios · Statistical downscaling ·
Human mortality · Future air pollution · Acclimatization ·
South–central Canada

Introduction

There is a growing consensus that global climate change will adversely affect human health as the intensity and frequency of heat waves and high air pollution episodes are projected to increase under future climate scenarios, (e.g., Last and Chiotti 2001; Riedel 2004; Meehl and Tebaldi 2004; Medina-Ramón and Schwartz 2007). As IPCC

(2007) pointed out, increased heat waves could increase risks of human mortality and morbidity, with *very likely* likelihood of occurrence in the middle to late of this century (90% to 99% probability). A number of the previous studies have projected that future heat-/air pollution-related human mortality could increase from the current conditions (Table 1). Of these studies, in terms of methodology, there are two major schemes: (1) epidemiological approach and

Table 1 Examples of previous studies on climate change impacts on human health

Study	Methodology	Major findings	Study area
Future increased heat and human health			
Kalkstein 1991	Threshold temperature Monthly GCM outputs	Heat-related mortality at the time of CO ₂ doubling could be 6-time higher than the current rates	15 US cities
Kalkstein & Greene 1997	Synoptic weather typing— multiple regression Daily GCM outputs	Study-area averaged increase in heat risks could range from 8% to 125% for the different GCM scenarios	44 US cities
Chiotti et al. 2002	Threshold temperature Daily GCM outputs	Heat-related mortality by 2030 could be several times higher than the current figures	Toronto, Canada
Dessai 2003	Threshold temperature & nonlinear regression Daily RCM outputs	Heat-related mortality could increase by 35% to 600% by the 2050s, compared to the period 1980–1998	Lisbon, Portugal
Knowlton et al. 2007	Threshold temperature Outputs of a global-to-regional climate system	Heat-related mortality by the 2050s could increase by 70% (ranging from 47% to 95%) from the figures in the 1990s	31 counties, New York, USA
Takahashi et al. 2007	Threshold temperature— multiple regression Daily GCM outputs	Heat-related mortality by the 2090s could increase by 100%–1,000% from the current figures of the 1990s	Over the world
Doyon et al. 2008	Generalized linear Poisson regression Daily GCM outputs	Summertime mortality could increase about 2% by 2020 and about 10% by 2080 from the current condition	Three cities, Quebec, Canada
Population acclimatization to the increased heat			
Kalkstein & Greene 1997	Technique of “analog cities”	Acclimatization could reduced future heat-related mortality by 20–40%	44 US cities
Dessai 2003	Dose–response relationship	Heat-related mortality by the 2050s could be reduced by 40–54% if the population is fully acclimatized	Lisbon, Portugal
Hayhoe et al. 2004	Linear regression within five hottest summer vs. all summers	Acclimatization could lower heat-related mortality by 20–25% by the 2080s	Los Angeles, USA
Knowlton et al. 2007	Generalized additive model with analog cities	Heat-related mortality by the 2050s could be reduced by 25%	31 counties, New York, USA
Future increased air pollution and human health			
Lashof et al. 2004	US air pollution model (CMAQ), GCM model (GISS), regional climate model (MM5)	Study area averaged O ₃ -related mortality and asthma hospital admissions could increase by 0.3% and 2.7% by the 2050s from the current condition, respectively	15 Eastern US cities
Knowlton et al. 2004	US air pollution model (CMAQ), GCM model (GISS), regional climate model (MM5)	The O ₃ -related mortality could increase by a median 4.5% by the 2050s from the 1990s, across the study area. If considering population growth and anthropogenic O ₃ precursor emission increases, the corresponding increase could be 60%	31 counties, New York, USA
Bell et al. 2006	Concentration–response functions Two emission scenarios	The economic value of the avoided health impacts of air pollution is about \$21 to \$165 billion by 2020	Three Latin American cities

(2) synoptic climatological approach. For each of the schemes, there are two main methods. The epidemiological approach is achieved by (a) time series analysis by Poisson regression or generalized additive models and (b) case-crossover analysis. The synoptic climatological approach principally involves (a) synoptic weather typing and (b) threshold temperature to define heat waves (Gosling et al. 2008).

Since a population might acclimatize to increased heat, some studies have attempted to evaluate acclimated mortality. If complete acclimatization is achieved, projected global climate warming might have little impact on heat-related mortality. Kalkstein (1991) pointed out that partial acclimatization estimation is probably more realistic, since changes in a city's physical structure may lag far behind human physiological adjustments. Two procedures were developed in the 1990s to measure acclimated mortality: (1) the technique of "analog cities" (Kalkstein 1991) and (2) comparing heat-related mortality rates during heat waves in both cool and hot summers (Nichols et al. 1995). The first method assumes that acclimatization can be assessed by heat-related mortality derived from the analog cities that currently possess a climate similar to the projected future climate of the city in question. Unfortunately, analog cities cannot duplicate the demographics and urban structure of the target city. The second method assumes that, if people acclimatize, they would react to heat to a greater extent during cooler summers, when heat waves are infrequent, than they would during hotter summers, when heat waves are a common occurrence.

In the previous studies on climate change and human health, projections from global climate models (GCM) or regional climate models (RCM) are most commonly used as future climates of this century. However, few studies have used the statistical (empirical) downscaling to analyze local health impacts of climate change. It is well known that statistical downscaling is able to derive station-scale future climate data, which might be more suitable for local climate change impacts analysis than raw outputs of GCMs and RCMs. In the light of this concern, this study used a statistical downscaling approach to derive hourly/daily future climate information for each of the selected cities.

In addition, as described in Part I (Cheng et al. 2009), a combination of automated synoptic weather typing and various regression methods was used to project future daily weather types and air pollution levels. All these future information is essential for this study to project the future heat-/cold-/air pollution-related mortality.

Data sources and treatment

Historical observations used in Part I (Cheng et al. 2009), including meteorological, air pollution, and mortality data, were also used in this study. In addition, this study has used the US National Centers for Environmental Prediction (NCEP) upper-air reanalysis data and five GCM outputs (Table 2). The NCEP reanalysis data were used to develop two types of the models for the study: (1) elevated mortality prediction models associated with temperature extremes and air pollution and (2) hourly/daily downscaling transfer functions. To combine the gridded reanalysis data with the surface weather observations, the reanalysis data were interpolated to the airport weather station of each selected city using the inverse-distance method (Shen et al. 2001). To estimate possible impacts of future climate change on human mortality, the GCM model outputs were used in the statistical downscaling transfer functions to derive future climate data for two time periods 2040–2059 and 2070–2089, representing the 2050s and 2080s. In addition to future time periods, the downscaled GCM control runs (1961–2000) were used in the study to correct the GCM model bias. The detailed information, regarding data sources, variables, and record length, is described in Table 2.

Future synoptic weather types and air pollution concentrations

To estimate future climate change impacts on human mortality due to increased heat and changes in air pollution concentrations, future climate data, synoptic weather types, and air pollution concentrations are required for this study. The principal methods and steps used in this study are

Table 2 Data used in the study, in addition to historical observations of meteorological, air pollution, and mortality data used in Part I (Cheng et al. 2009)

Description	Period	Variable	Source
Reanalysis data: Six-hourly upper-air levels (925, 850, 700, 600, 500 hPa) at 01:00, 07:00, 13:00, and 19:00 local standard time	1961–2000	Air temperature (°C) Dew point temperature (°C) U-wind and V-wind (m s^{-1})	US National Centers for Environmental Prediction (NCEP) Website
GCM outputs: Daily surface and upper-air levels (925, 850, 700, 600, 500 hPa)	1961–2000 2040–2059 2070–2089	Air temperature (°C) Sea-level air pressure (hPa) U-wind and V-wind (m s^{-1})	IPCC IS92a: Canadian GCM—CGCM1 IPCC SRES A2/B2: Canadian GCM—CGCM2 US GCM—GFDL-R30

summarized in Fig. 1. This section is comprised of three subsections: (1) statistical downscaling, (2) projection of future weather types, and (3) estimation of future air pollution concentrations. Since these results were published already as part of the project, the relevant methods and results are briefly described here, for detailed information, refer to publications (Cheng et al. 2007a, 2007b, 2008).

Statistical downscaling

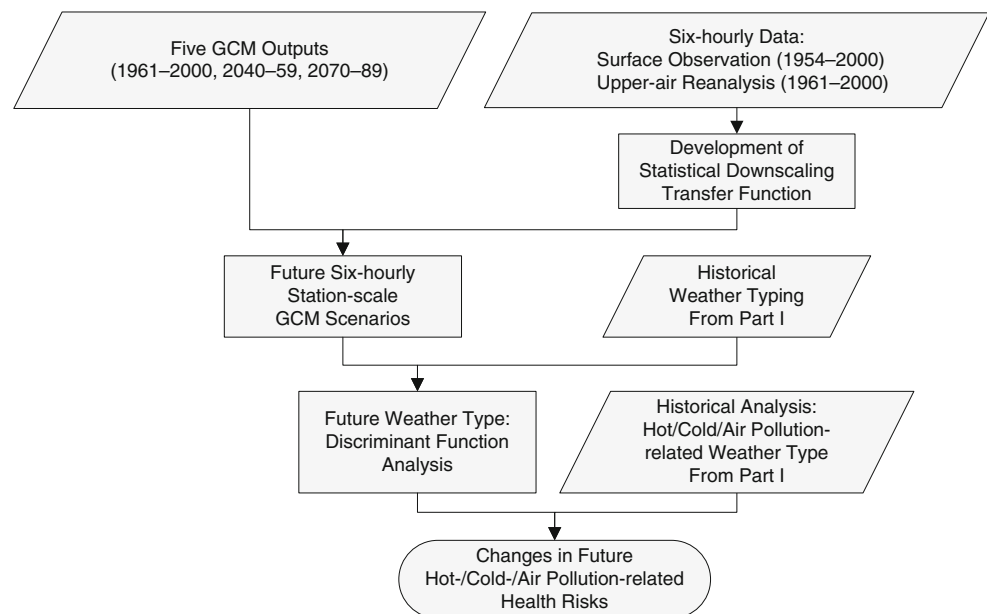
As part of this research, Cheng et al. (2008) have developed a regression-based statistical downscaling method to spatially downscale daily GCM outputs to the four selected weather stations and temporally downscale daily scenarios to the hourly. A number of regression methods (i.e., multiple stepwise regression, cumulative logit regression, orthogonal regression, and autocorrelation correction regression) were employed to derive station-scale hourly/daily future climate information for the standard meteorological variables that are essential to analyze health impacts of climate change. Performance of the downscaling methods was evaluated by (1) analyzing model R^2 s, (2) validating downscaling transfer functions using a cross-validation scheme, (3) comparing data distributions and diurnal/seasonal variations of downscaled GCM control runs with observations over a comparative time period of 1961–2000, and (4) examining extreme characteristics. The results showed that regression-based downscaling methods performed very well in deriving station-scale hourly/daily climate information. For example, the hourly downscaling transfer functions for most of weather elements (e.g., air

temperatures, dew point, and air pressure) possess the model $R^2 > 0.95$.

Projection of future weather types

Future weather types projected by Cheng et al. (2007b), as part of the research, were used in the current study. To determine future daily weather types, principal components analysis and discriminant function analysis were employed with downscaled six-hourly future climate data. Component scores for each of the future days were calculated by multiplying the post-eigenvector matrix (using the model developmental dataset in Part I—Cheng et al. 2009) by the standardized future weather data matrix. To effectively compare component scores from both historical and future datasets as well as to remove the GCM model bias, future downscaled weather data were standardized using the mean and standard deviation of downscaled GCM control runs. Using the centroids of the predetermined weather types as seeds, discriminant function analysis can assign each of the future days into one of the predetermined historical weather types based on component scores. This method is proposed to be an appropriate approach in light of a changing climate since discriminant function analysis could assign future days with a simulated higher temperature beyond the range of the historical observations into the hottest weather group. These cases could be rare (typically $<1\%$ of the future days) because many of the future days could be more frequently warmer than the current past rather than actual truly warmer than ever observed (Dettinger et al 2004; Hayhoe et al. 2004). The frequency of occurrence and intensity of the

Fig. 1 Flow chart of methodologies and steps used in the study



hottest weather group could increase under the future climate.

Percentage occurrences of the eight weather groups are plotted in Fig. 2, as shown by observations and an average of three CGCM control runs for the period 1961–2000 as well as an average of five GCM scenarios for the 2050s and 2080s. The ten weather groups described in Part I (Cheng et al. 2009) include three hot, one cold, five pollutant-related, and one other groups. In this study, the three hot weather groups were combined as one large hot weather group. From Fig. 2 it is immediately apparent that the frequency of the hot weather group could double and triple by the 2050s and 2080s, respectively, across the study area; meanwhile, the frequency of the cold weather group could markedly decrease under future climate conditions. For all pollutants except ozone (O₃), the percentage frequency of the pollutant-related weather groups is projected to be similar in the future to that witnessed currently. The frequency of the O₃-related weather group could noticeably decrease since, due to a changing climate, some of the days that currently fall into the O₃-related weather group could, in the future, fall into the hot weather group. Similarly, the frequency of the comfortable weather group could decrease slightly across the study area.

Estimation of future air pollution concentrations

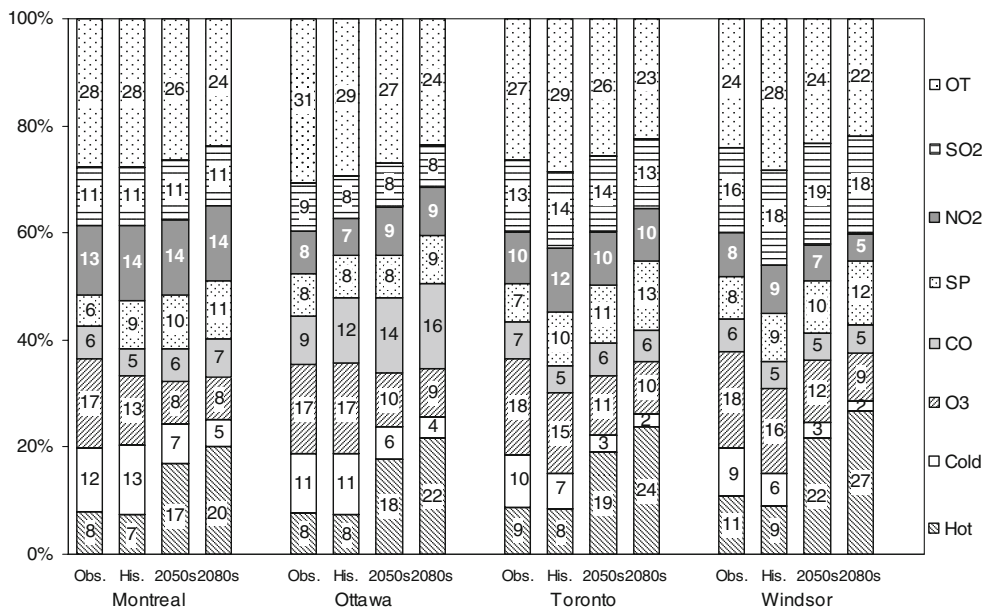
In addition to future six-hourly downscaled climate data and weather types, future daily air pollution concentrations are essential in this study for projection of climate change impacts on human health. As part of the research, Cheng et al. (2007b) have recently projected future daily air pollution

concentrations for the four selected cities in south-central Canada, which were used in the current study. To project future daily air pollution levels, automated synoptic weather typing and robust orthogonal stepwise regression were applied altogether with downscaled future hourly GCM climate information.

Performance of the within-weather-group air pollution simulation models was evaluated by analyzing model R²s and validating the models using the independent dataset—one third of the total years selected randomly (Cheng et al. 2007a). There was a significant correlation between observed daily mean air pollution concentrations and model predictions. About 20%, 50%, and 80% of the 80 prediction models across the study area possessed R² values ≥0.7, 0.6, and 0.5, respectively. The results of model validation were similar to those of model development, with slightly smaller model R². In addition, the air pollution simulation models were evaluated by comparing statistical properties of air pollution concentrations driven by downscaled GCM control runs with observations over a comparative time period of 1961–2000. The evaluation results have indicated that the air pollution simulation models performed very well in reproducing historical daily air pollution concentrations using downscaled GCM control runs.

To estimate future pollution levels, three future pollutant emission control scenarios were considered: Scenario I—emissions decreasing 20% by 2050, Scenario II—emissions remaining at the same level as at the end of the twentieth century, and Scenario III—emissions increasing 20% by 2050. The future estimate results showed that under future pollutant emission Scenario II, averaging the five GCM scenarios across

Fig. 2 Percentage occurrences of the eight weather groups (hot, cold, five pollutant-related, OT—other) as shown by observations (*Obs.*) and an average of three CGCM control runs (*His.*) for the period 1961–2000, as well as an average of five GCM scenarios for the 2050s and 2080s



the four selected cities, warm season 6-month (April–September) daily mean O₃ concentrations could increase 2.7 ppb by the 2050s and 4.0 ppb by the 2080s compared to 1990s levels. Due to the changing climate alone, the number of days within the high-O₃-level category (1-h maximum ≥ 81 ppb) could increase by 50% by the 2050s and 100% by the 2080s. The corresponding number of days within the low-O₃-level category (1-h maximum ≤ 50 ppb) could decrease by 6% and 9%; the number of days within the moderate-O₃-level category (in between the high and the low) could increase by 35% and 40%. The changing climate could also impact future air pollution concentrations of the remaining pollutants [i.e., carbon monoxide (CO), nitrogen dioxide (NO₂), sulphur dioxide (SO₂), and suspended particulates (SP)] even if future pollutant emission levels remain the same as at the end of the twentieth century. The number of days within the high pollution level category (one standard deviation above the overall mean, based on 1981–2000 levels) could increase by 20–40% by the middle and late part of this century. On the other hand, the corresponding number of days within the low pollution level category (below the 1981–2000 mean) could decrease in the future; the magnitude of this change varies among the pollutants.

Elevated mortality predictions

To project future elevated extreme temperature-/air pollution-related mortality, within-weather-type elevated mortality prediction models are needed. The orthogonal stepwise regression procedure was employed on all days within each of the identified eight weather groups to develop elevated mortality prediction models. Before developing the models, within each of the eight weather groups, the data were regrouped using the SAS Rank procedure (SAS Institute Inc. 1999). A key variable used for ranking data was different for each of the eight weather groups. In hot and cold weather groups, 15:00 local standard time (LST) temperature was used to sort the data from lowest to highest; then the days were put into ranking groups with a roughly equal number of days in each ranking group. The afternoon was chosen as the time to take the temperature reading because the analysis revealed this to be the time when the strongest relationships with elevated mortality exist; this finding is consistent with previous studies (e.g., Smoyer et al. 1999; Davis et al. 2003). In air pollution-related weather groups, an air pollutant was used to rank the data for that pollutant-related weather group; for example, O₃ was used to rank the data for O₃-related weather group. For comfortable (“other”) weather group, five air pollutants were tested for ranking the data; the model with the highest R^2 was used for the analysis. As a result of testing, O₃ was selected to rank data for development of the elevated

mortality prediction model in comfortable weather group for Montreal, and SO₂ for the rest of the cities.

The advantage of using the ranking procedure is that it allows enhancement of the relationships between elevated mortality and a certain factor within a particular weather group, while also minimizing the impacts of other factors. For each weather group, nine different rankings (20 to 60 groups, in intervals of five) were tested to develop nine models; the model with the highest R^2 was used in the analysis. The independent variables, including weather and air pollution predictors, are shown in Table 3. To avoid multi-collinear effects among explanatory predictors, the orthogonal stepwise regression, combination of principal components analysis and multiple stepwise regression, was used in the study.

In addition to testing different rankings, different lag times (0–4 days) were also tested to develop elevated mortality prediction models; the model with the highest R^2 was used for the analysis. Across the study area, the no-lag-time prediction model in the hot weather group was usually more significant than other lag-time models. This finding is consistent with that of previous studies (e.g., Dessai 2002; Rainham and Smoyer-Tomic 2003; Sheridan and Kalkstein 2004), although other studies identified a 1- or 2-day lag between the mortality response and a heat event (e.g., Rogot and Padgett 1976; Davis et al. 2003). For the rest of the weather groups (e.g., pollution-related or cold), most of the prediction models were more significant with 1-day lag or no lag time between the deaths and the environmental factors.

The results of within-weather-group elevated mortality prediction models showed that many weather variables (such as surface and upper-air temperatures, humidex—

Table 3 Predictors used in principal components analysis for development of elevated mortality prediction models

05:00, 15:00	Surface temperature
05:00, 15:00	Humidex—Canadian summer temperature and humidity index (warm season)
05:00, 15:00	Wind chill index (cold season)
05:00, 15:00	Sea level air pressure
05:00, 15:00	Wind speed
05:00, 15:00	Total cloud cover
05:00, 15:00	Inter-diurnal temperature change
05:00, 15:00	Inter-diurnal humidex change
05:00, 15:00	Inter-diurnal wind chill index change
01:00, 13:00	Mean temperature of three upper-air levels (850, 700, 500 hPa)
	Daily mean, 1-h maximum ozone concentration
	Daily mean, 1-h maximum sulphur dioxide concentration
	Daily mean, 1-h maximum nitrogen dioxide concentration
	Daily mean, 1-h maximum suspended particles concentration
	Daily mean, 1-h maximum carbon monoxide concentration

Times listed are local standard time (LST)

Canadian summer temperature and humidity index, wind chill) and all selected pollutants (O_3 , CO , NO_2 , SO_2 , SP) were significantly associated with elevated mortality in the different weather groups. The regression results showed that there were usually strong relationships between elevated mortality and model predictions for most weather groups across the study area. Of the 32 models in total, 7, 17, and 23 models possessed an R^2 of at least 0.6, 0.5, and 0.4, respectively. These models have the potential for both short-term prediction and long-term projection of elevated mortality associated with current and future climate and air pollution conditions. The relationships between elevated mortality and weather/air pollution predictors, across the study area, are outlined as follows:

1. Thermal and moisture weather variables were significantly associated with elevated mortality in the hot weather group; and it was found that the contribution of O_3 to elevated mortality was also statistically significant for the selected cities, except Montreal.
2. In cold weather group, low temperatures, low wind chill equivalent temperatures, and high air pollution concentrations contributed to elevated mortality.
3. In five pollutant-related weather groups, both air pollution concentrations and weather conditions were significantly important to elevated mortality.
4. In comfortable weather group, air pollution levels, but not weather variables, were significantly associated with elevated mortality.

Changes in future elevated mortality without acclimatization

Future elevated mortality was projected in this section when acclimatization was not taken into account. Following determination of potential changes in the number of days within weather types, weather characteristics, and air pollution concentrations as a result of climate changes, potential changes in future elevated mortality can be quantitatively estimated. In this study, two independent approaches were used to assess climate change impacts on elevated mortality: (1) comparing future and historical frequencies of the weather groups and (2) applying within-weather-group elevated mortality prediction models with future downscaled climate data. Before assessing future elevated mortality, it is necessary to ascertain whether the methods are suitable for the assessment by comparing elevated mortality driven by the downscaled GCM control runs with observations over a comparative time period (1961–2000). As shown in Table 4, the results indicated that the methods are suitable since there are small differences between both estimates derived from downscaled GCM control runs and observations. These differences could be resulted from the GCM bias and were used to adjust estimates of future elevated mortality.

The first method depends on changes in the frequency of future weather groups alone. Future within-weather-group elevated mortality is assumed to be directly proportional to corresponding historical elevated mortality and change in

Table 4 Elevated mortality resulting from weather observations (Obs) and Canadian GCM control runs (C-1: CGCM1, C-A2: CGCM2-A2, C-B2: CGCM2-B2)

Weather group	Data	Number of Elevated Mortality							
		Montreal		Ottawa		Toronto		Windsor	
		Est. I	Est. II	Est. I	Est. II	Est. I	Est. II	Est. I	Est. II
Hot	Obs	121		40		120		36	
	C-1	117	112	41	43	132	113	31	37
	C-A2	110	111	38	40	124	108	29	34
	C-B2	110	110	38	41	125	107	29	34
Cold	Obs	142		53		105		32	
	C-1	157	165	53	62	87	97	22	26
	C-A2	160	169	56	65	63	75	22	27
	C-B2	160	169	54	63	62	73	22	27
Air pollution and other	Obs	818		368		822		258	
	C-1	731	829	360	361	803	736	272	289
	C-A2	736	831	358	364	833	751	275	290
	C-B2	737	830	359	364	833	751	275	285
Total	Obs	1,082		462		1,047		327	
	C-1	1,005	1,106	454	465	1,022	946	325	352
	C-A2	1,006	1,111	452	469	1,020	934	326	351
	C-B2	1,007	1,109	451	468	1,020	931	326	346

Est. I estimate I based on changes in frequency of weather groups, *Est. II* estimate II based on elevated mortality prediction algorithms

frequency of future weather groups. To support this assumption, the relationships between annual total elevated mortality and number of days, within each of the eight weather groups, were evaluated for the period 1954–2000 across the study area. The results show that the relationships are statistically significant for all weather groups, except for the comfortable weather group in some cities. Elevated mortality within a weather group generally increases with the number of days. For example, in

Toronto, as shown in Fig. 3, the daily heat- and cold-related mortality increases by about 4.0 and 3.5 per 1 day increase in the hot and cold weather groups, respectively. Similar results were discovered for the rest of the selected cities as well. The second method applied within-weather-group elevated mortality prediction algorithms to project future elevated mortality, using projected future daily air pollution and downscaled hourly climate data. Future climate and air pollution data were ranked according to

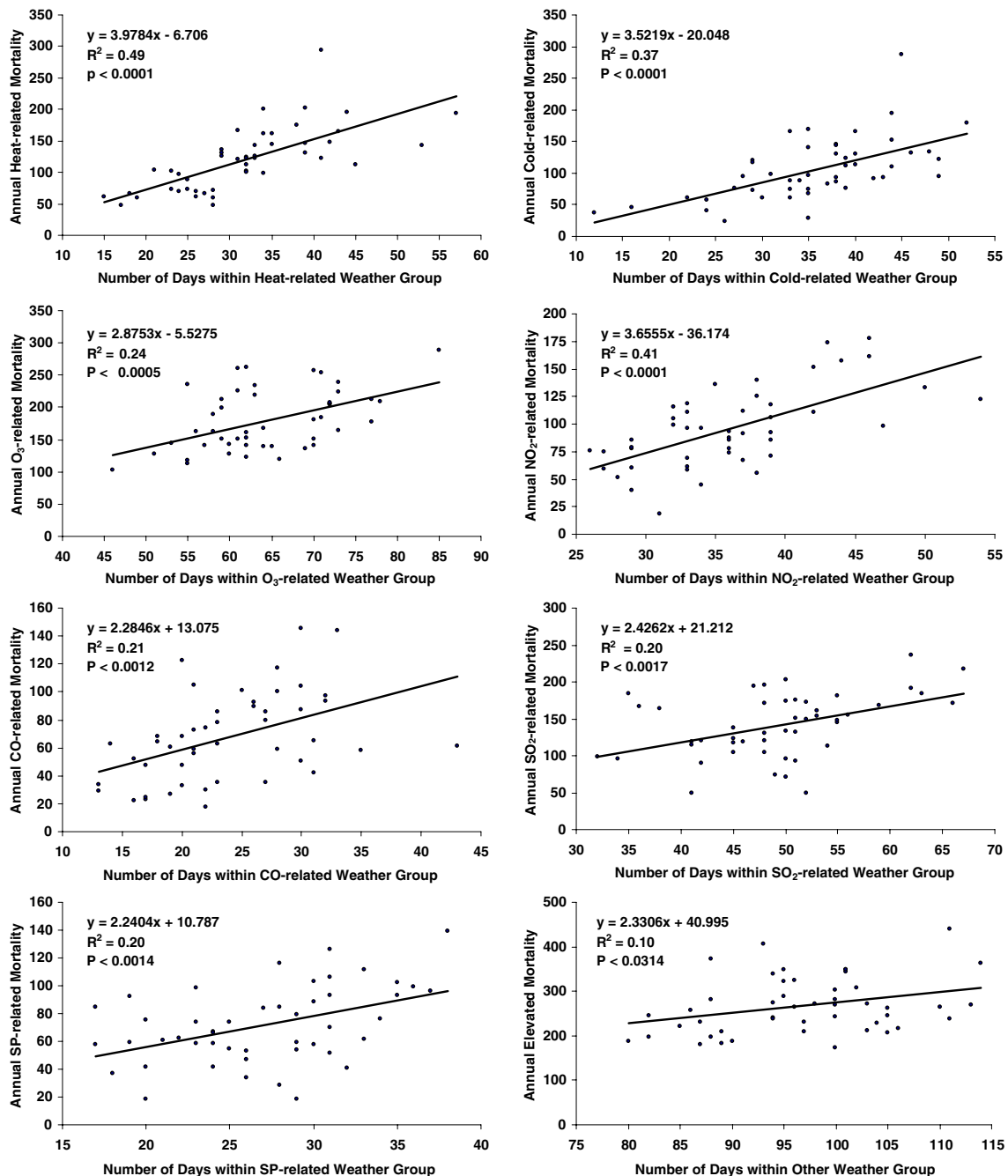


Fig. 3 The relationships between annual elevated mortality and number of days within each of the eight weather groups for the period 1954–2000 in Toronto

the same criteria as were the historical observations. Following estimation of future elevated mortality for each weather group, increase and decrease percentages of future hot-, cold-, and air pollution-related mortality can be determined accordingly.

The results on changes in elevated mortality for the five future climate change scenarios, derived from both methods, were very similar. However, the magnitude of increases in future heat-related mortality resulting from the second method was slightly greater than that from the first. From Fig. 4, across the study area, heat-related mortality is projected to be more than double by the 2050s and triple by the 2080s. Additionally, cold-related mortality could dramatically decrease in the future. For example, on average across the five GCM scenarios, by the 2050s cold-related mortality could decrease by about 45% for the two northern cities and by about 60% for the two southern cities; by the 2080s, corresponding decrease rates could be more similar across the study area (60–70%).

To assess future air pollution-related mortality, the hot weather groups should be included, since they possessed the highest O₃ level of all the weather types. The combination of the hot and O₃-related weather groups was used to develop the O₃-related mortality prediction model

for estimating future O₃-related mortality. Ozone concentration was used to rank the data for development of the O₃-related mortality prediction model in order to emphasize O₃ impacts and minimize other factors (e.g., heat). For other pollutants, the same procedure was applied except that a particular important air pollutant was used to rank the data. Future O₃-related mortality and other air pollutant-related mortality were combined and showed in Fig. 5. The percentage increases in future air pollution-related mortality become greater when moving from southwest to northeast. For example, averaging the five GCM scenarios, air pollution-related mortality in Montreal is projected to increase by 30–40% by the 2050s and 40–55% by the 2080s for the three air pollution policy emission scenarios; however, the corresponding increases were 15–20% and 20–30% for Toronto. These increases would be largely driven by increases in O₃-related elevated mortality.

Assessments of population acclimatization to the increased heat

Could the population in south-central Canada potentially acclimatize to the increased heat from global warming? The

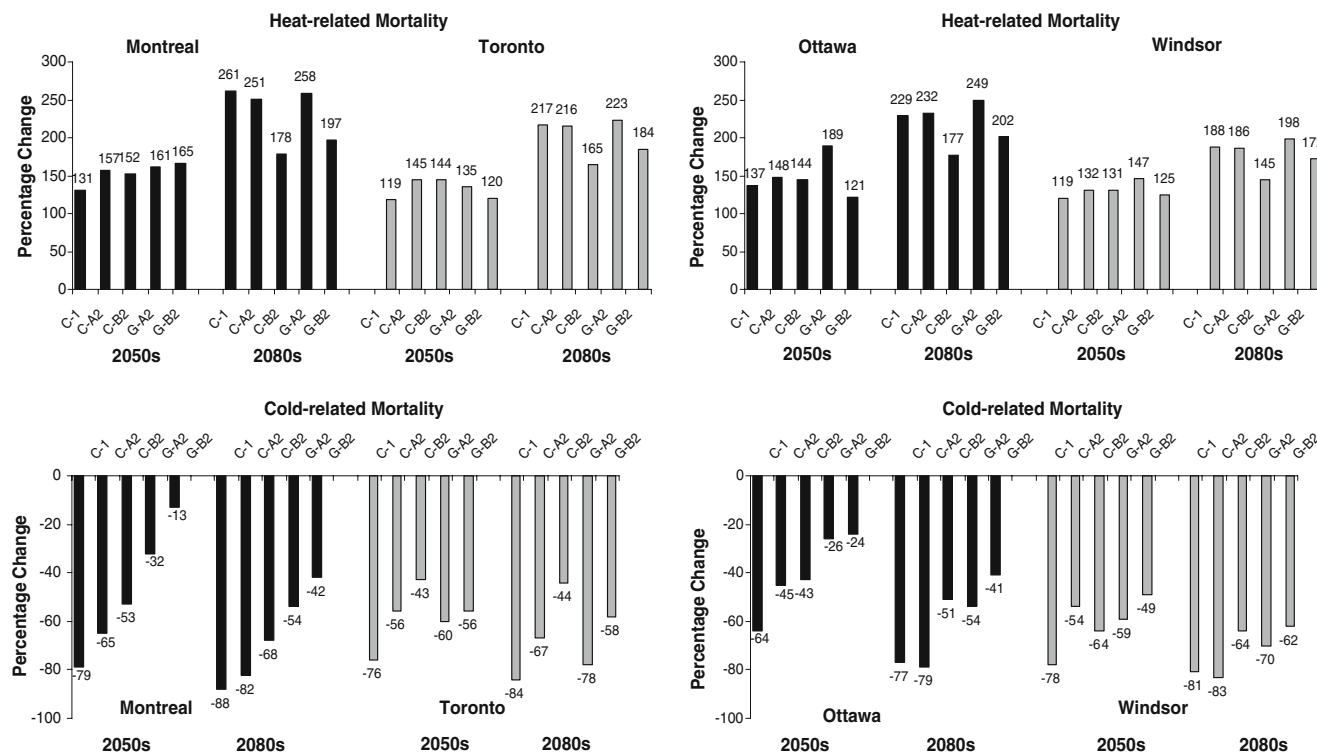
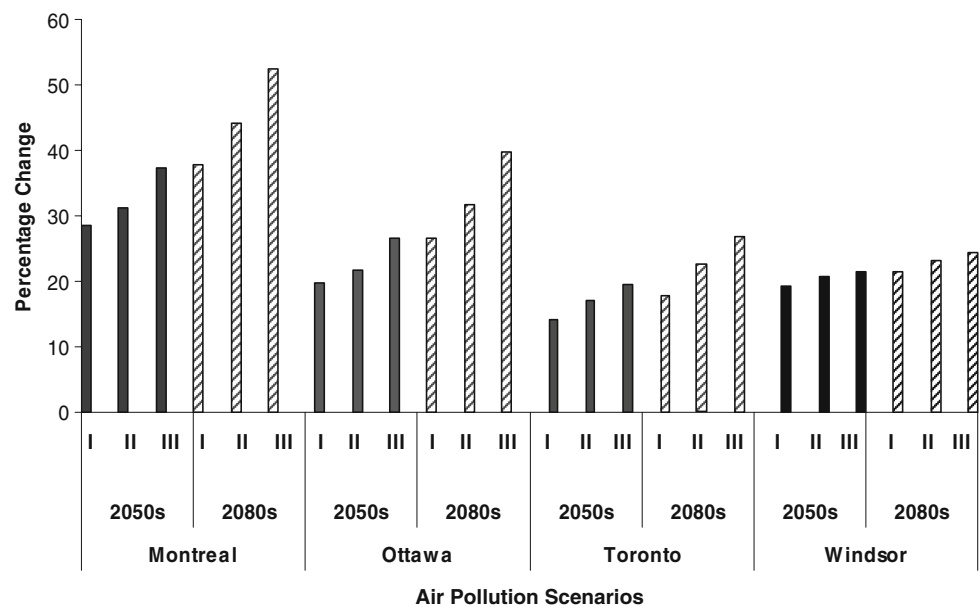


Fig. 4 Estimate II (based on elevated mortality prediction algorithms with downscaled future climate data and projected future weather groups and air pollution levels): percentage changes in future mean annual total heat-related (*top*) and cold-related (*bottom*) mortality (2050s and 2080s) from the average condition of the period 1954–

2000. Values of 100% and 200% indicate that future mortality could double and triple; and a value of –100% indicates that the event would decrease to zero (C-1 CGCM1-IS92a, C-A2 CGCM2-A2, C-B2 CGCM2-B2, G-A2 GFDL-A2, G-B2 GFDL-B2)

Fig. 5 Percentage changes in future air pollution-related mortality (2050s and 2080s) from the average condition of the period 1954–2000 resulting from averaging the five GCM scenarios. Three future pollutant emission scenarios: *I* decrease by 20% (32%) by 2050 (2080), *II* remain at the same level as at the end of the twentieth century, and *III* increase by 20% (32%) by 2050 (2080)



answer is yes, since population will acclimatize to changing climate via a range of behavioural, physiological, and technological adaptations. To quantitatively analyze acclimatization, the method used in Nichols et al.'s study (1995) was adapted for this study. The difference in daily mean deaths within the hot weather groups between cooler and hotter summers was assumed to be a result of the population acclimatization to the increased heat. It is assumed that, if people adapt to global warming, they could react to heat to a greater extent during cooler summers, when heat waves are infrequent, than they would during hotter summers, when heat waves are more frequent. If the results indicate that more people die per hot day during a cooler summer, and fewer die per hot day during a hotter summer, it would conclude that there has been some degree of acclimatization during the warmer summers. For each of the selected cities, five cool and five hot summers were selected for assessment of acclimatization. Two criteria were used for selecting a cool or hot summer: (1) the frequency of the extreme hot weather group (Hot1) and (2) the mean temperature within the hot weather groups. The hot and cool summers were selected when the hot weather types most and least frequently occurred during the period 1953–2000, respectively; mean temperature during heat waves should be similar in both cool and hot summers.

The differences in daily mean deaths within the hot weather group between the selected five cool and five hot summers were 1.07, 0.31, 1.08, and 0.17 for Montreal, Ottawa, Toronto, and Windsor, respectively. These differences were assumed to be a result of the population acclimatization to the increased heat and were used to discount future estimated daily heat-related mortality for each day within the future projected hot weather group. The percentage increases in future heat-related mortality result-

ing from averaging the five GCM scenarios are presented in Table 5 for both non-acclimatization and acclimatization. When population acclimatization was considered, projected future heat-related mortality was significantly reduced by 40% from results of non-acclimatization across the study area. By the 2050s and 2080s, heat-related mortality, considering people acclimatization, is projected to increase by about 70–90% and 120–140% from the average condition of the period 1954–2000, respectively.

The results on population acclimatization to the increased heat, reducing heat-related deaths by 40% in the middle and late part of this century, are consistent to some degree with the findings of previous studies. As shown in Table 1, acclimatization effects are projected to reduce future heat-related mortality by 20–40% in the United States (Kalkstein and Greene 1997; Hayhoe et al. 2004; Knowlton et al. 2007) and by 40–54% in Lisbon, Portugal (Dessai 2003). These results clearly indicate that the degree of population acclimatization to increased heat rises geographically from the south to the north. This implies that people in higher latitudes might have more potential to acclimatize to increased heat than those in lower latitudes.

Uncertainties of the study

In many ways, climate change represents a different kind of problem than many professions typically address. It is highly complex, interdisciplinary, and in certain need of more integrated and varied science and policy than many of today's problems require. Climate-change issues require that new approaches and a recasting of existing scientific methods be developed to deal with potential health implications. Many uncertainties remain in the assessment

Table 5 Five-GCM-ensemble percentage increases in future estimated heat-related mortality from the average condition of the period 1954–2000

Estimate method	Acclimatization	Percentage increases in future estimated heat-related mortality							
		Montreal		Ottawa		Toronto		Windsor	
		2050s	2080s	2050s	2080s	2050s	2080s	2050s	2080s
Est. I	Non-acclimatization	123	168	132	188	130	195	110	154
	Acclimatization	67	101	83	127	67	115	71	107
Est. II	Non-acclimatization	148	224	148	217	129	197	128	175
	Acclimatization	92	158	98	156	66	117	89	128

Values of 100% and 200% indicate that heat-related mortality would double and triple, respectively

Est. I estimate I based on changes in frequency of weather groups, *Est. II* estimate II based on elevated mortality prediction algorithms

of potential health impacts of climate change. These uncertainties include “recognition that various other changes in social, economic, demographic, technological, and health care circumstances would unfold over coming decades and that these developments would ‘condition’ the impact of climatic and environmental changes on human health” (IPCC 2001). Many of these factors, especially population growth and age structure changes, were not directly taken into account in the current study. As a result, it is most likely that the estimate of future heat-/cold- and air pollution-related mortality from this study could represent the lower bound value for the study area. Additional research is needed to address the impacts of these factors and adaptation measures on future elevated mortality.

Considerable effort was made in this study to transfer GCM-scale scenarios to station-scale future climate information using statistical downscaling transfer functions (refer to Cheng et al. 2008). Through the downscaling process, most of the GCM model bias was removed using the past 50-year historical relationships between regional-scale predictors and station-scale weather elements. As a result, the quality of future climate data, following downscaling, was much improved. For example, data distribution (including extreme events) of the downscaled GCM control runs was similar to that of the observation over a comparative time period (1961–2000). However, conclusions made in this study about health impacts of climate change still relied on GCM scenarios and, as a result, there is corresponding uncertainty about the study findings. Four major sources of uncertainty related to GCM scenarios (i.e., model structure, measurement error, variability, scaling) indicated by Katz (2002) could have an effect on the results of this study. Of them, the most important one comes from GCM modeling. Due to model size and complexity, the GCM models must have inevitably omitted some factors that affect climate (e.g., effects of the Great Lakes on southern Ontario weather). However, following application of the statistical downscaling method,

it seems that the uncertainty on future heat- and air pollution-related mortality projected from this study is reduced since the magnitudes of percentage increases in the future elevated mortality projections are very similar among the five GCM scenarios.

Conclusions

The overarching purpose of this study was to investigate the differential and combined impacts of extreme temperatures and air pollution on human mortality under future climates for four selected cities in south-central Canada (Montreal, Ottawa, Toronto, and Windsor). Synoptic weather typing used in the study was able to achieve this goal because of its ability to consider a complex set of meteorological variables altogether as a coherent index. The index can identify the various weather situations associated with temperature extremes and high air pollution episodes; and in turn, it facilitates to distinguish the differential and combined health impacts of oppressive heat, cold, and air pollution under the current and future climates. This study aims to provide decision makers with scientific information needed for improving the adaptive capacity of the health infrastructure to projected human health impacts of climate change. Given the results of this study, a national strategy on human health impacts should be given careful consideration since the health care system in Canada could become further stressed by climate change in the middle and late part of this century. The results of this study might be helpful in providing scientific information for the development of a national strategy on human health adaptation policies in response to projected global warming.

To estimate future extreme temperature- and air pollution-related mortality, downscaled future climate information, estimated future air pollution concentrations, and projection of future weather types were required in the

study. Following determination of this essential future information, future heat- /air pollution-related mortality can be quantitatively estimated. Averaging the five GCM scenarios and across the study area, the model projections were summarized as follows:

1. Heat-related mortality without consideration of population acclimatization to increased heat is projected to be more than double by the 2050s and triple by the 2080s.
2. When the population acclimatization to the increased heat was taken into account, projected future heat-related mortality could be reduced by 40%. By the 2050s, heat-related mortality is projected to increase by 70–90% and by the 2080s, by 120–140%.
3. By the 2050s, cold-related mortality is projected to decrease by about 45% for Montreal and Ottawa and by 60% for Toronto and Windsor; by the 2080s, the percentage decrease could be more similar across the study area (60–70%).
4. Air pollution-related mortality is projected to increase by about 20–30% by the 2050s and about 30–45% by the 2080s. This increase would be largely driven by increases in O₃-related elevated mortality.

Acknowledgments This study was funded through the Health Policy Research Program of Health Canada (6795-15-2001/4400011). The views expressed herein are solely those of the authors and do not necessarily represent the views or official policy of Health Canada or Environment Canada. The authors are grateful for the suggestions made by the Project Advisory Committee, which greatly improved the study. We also would like to thank two anonymous reviewers for providing detailed comments that significantly improved the original manuscript.

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References

- Bell ML, Davis DL, Gouveia N, Borja-Aburto VH, Cifuentes LA (2006) The avoidable health effects of air pollution in three Latin American cities: Santiago, São Paulo, and Mexico City. *Environ Res* 100:431–440 doi:10.1016/j.envres.2005.08.002
- Cheng CS, Campbell M, Li Q, Li G, Auld H, Day N, Pengelly D, Gingrich S, Yap D (2007a) A synoptic climatological approach to assess climate impact on air quality in south-central Canada. Part I: historical analysis. *Water Air Soil Pollut* 182:131–148 doi:10.1007/s11270-006-9327-3
- Cheng CS, Campbell M, Li Q, Li G, Auld H, Day N, Pengelly D, Gingrich S, Yap D (2007b) A synoptic climatological approach to assess climate impact on air quality in south-central Canada. Part II: future estimates. *Water Air Soil Pollut* 182:117–130 doi:10.1007/s11270-006-9326-4

- Cheng CS, Li G, Li Q, Auld H (2008) Statistical downscaling of hourly and daily climate scenarios for various meteorological variables in South-central Canada. *Theor Appl Climatol* 91:129–147 doi:10.1007/s00704-007-0302-8
- Cheng CS, Campbell M, Li Q, Li G, Auld H, Day N, Pengelly D, Gingrich S, Klaassen J, MacIver D, Comer N, Mao Y, Thompson W, Lin H (2009) Differential and combined impacts of extreme temperatures and air pollution on human mortality in south-central Canada. Part I: historical analysis. *Air Qual Atmos Health* doi:10.1007/s11869-009-0027-1
- Chiotti Q, Morton I, Maarouf A (2002) Towards an adaptation action plan: Climate change and health in the Toronto–Niagara Region. Summary for policy makers. *Pollution Probe*, Toronto, p 50
- Davis RE, Knappenberger PC, Michaels PJ, Novicoff WM (2003) Changing heat-related mortality in the United States. *Environ Health Perspect* 111:1712–1718
- Dessai S (2002) Heat stress and mortality in Lisbon Part I. Model construction and validation. *Int J Biomet* 47:6–12 doi:10.1007/s00484-002-0143-1
- Dessai S (2003) Heat stress and mortality in Lisbon Part II. An assessment of the potential impacts of climate change. *Int J Biomet* 48:37–44 doi:10.1007/s00484-003-0180-4
- Dettinger MD, Cayan DR, Meyer MK, Jeton AE (2004) Simulated hydrologic responses to climate variations and change in the Merced, Carson, and American River Basins, Sierra Nevada, California, 1900–2099. *Clim Change* 62:283–317 doi:10.1023/B:CLIM.0000013683.13346.4f
- 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 doi:10.1186/1476-072X-7-23
- Gosling SN, Lowe JA, McGregor GR, Pelling M, Malamud BD (2008) Associations between elevated atmospheric temperature and human mortality: a critical review of the literature. *Clim Change* 92:299–341 doi:10.1007/s10584-008-9441-x
- Hayhoe K, Cayano D, Field CB, Frumhoff PC, Maurer EP, Miller NL, Moser SC, Schneider SH, Cahill KN, Cleland EE, Dale L, Drapek R, Hanemann MR, Kalkstein LS, Lenihan J, Lunch CK, Neilson RP, Sheridan SC, Verville JH (2004) Emissions pathways, climate change, and impacts on California. *Proc Natl Acad Sci U S A* 101:12422–12427 doi:10.1073/pnas.0404500101
- IPCC (2001) *Climate change 2001: Impacts, adaptation, and vulnerability*. Cambridge University Press, Cambridge, p 1032
- IPCC (2007) Summary for policymakers. 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 intergovernmental panel on climate change. Cambridge University Press, Cambridge
- Kalkstein LS (1991) Potential impact of global warming: Climate change and human mortality. In: Wyman RL (ed) *Global climate change and life on earth*. Routledge, Chapman and Hall, New York, pp 216–223
- Kalkstein LS, Greene JS (1997) An evaluation of climate/mortality relationships in large U.S. cities and the possible impacts of a climate change. *Environ Health Perspect* 105:84–93 doi:10.2307/3433067
- Katz RW (2002) Techniques for estimating uncertainty in climate change scenarios and impact studies. *Clim Res* 20:167–185 doi:10.3354/cr020167
- Knowlton K, Rosenthal JE, Hogrefe C, Lynn B, Gaffin S, Goldberg R, Rosenzweig C, Civerolo K, Ku J-Y, Kinney PL (2004) Assessing ozone-related health impacts under a changing climate. *Environ Health Perspect* 112:1557–1563
- Knowlton K, Lynn B, Goldberg RA, Rosenzweig C, Hogrefe C, Rosenthal JK, Kinney PL (2007) Projecting heat-related mortal-

- ity impacts under a changing climate in the New York City Region. *Am J Public Health* 97:2028–2034 doi:[10.2105/AJPH.2006.102947](https://doi.org/10.2105/AJPH.2006.102947)
- Lashof DA, Patz JA, Kinney PL, Bell ML, Ellis H, Goldberg R, Hogrefe C, Khoury S, Knowlton K, Rosenthal J, Rosenzweig C, Ziska L (2004) Heat advisory: How global warming causes more bad air days. A report of natural resources defense council, p.24
- Last J, Chiotti Q (2001) Climate Change and Health. *ISUMA* 2(4):62–69
- Medina-Ramón M, Schwartz J (2007) Temperature, temperature extremes, and mortality: a study of acclimatisation and effect modification in 50 US cities. *Occup Environ Med* 64:827–833 doi:[10.1136/oem.2007.033175](https://doi.org/10.1136/oem.2007.033175)
- Meehl GA, Tebaldi C (2004) More intense, more frequent, and longer lasting heat waves in the 21st century. *Science* 305:994–997 doi:[10.1126/science.1098704](https://doi.org/10.1126/science.1098704)
- Nichols MC, Kalkstein LS, Cheng CS (1995) Possible human health impacts of a global warming. *World Resour Rev* 7:77–103
- Rainham DGC, Smoyer-Tomic KE (2003) The role of air pollution in the relationship between a heat stress index and human mortality in Toronto. *Environ Res* 93:9–19 doi:[10.1016/S0013-9351\(03\)00060-4](https://doi.org/10.1016/S0013-9351(03)00060-4)
- Riedel D (2004) Chapter 9: Human health and well-being. In: Lemmen DS and Warren FJ (eds) Climate change impacts and adaptation: A Canadian Perspective Report, Government of Canada 153–169
- Rogot E, Padgett SJ (1976) Associations of coronary and stroke mortality with temperature and snowfall in selected areas of the United States, 1962–1966. *Am J Epid* 103:565–575
- SAS Institute Inc (1999) SAS Procedure Guide. Version 8. Cary, NC: SAS Institute Inc., p.1563
- Shen SSP, Dzikowski P, Li G, Griffith D (2001) Interpolation of 1961–97 daily temperature and precipitation data onto Alberta polygons of ecodistrict and soil landscapes of Canada. *J Appl Meteorol* 40:2162–2177 doi:[10.1175/1520-0450\(2001\)040<2162:IOD-TAP>2.0.CO;2](https://doi.org/10.1175/1520-0450(2001)040<2162:IOD-TAP>2.0.CO;2)
- Sheridan SC, Kalkstein LS (2004) Progress in heat watch-warning system technology. *Bull Am Meteorol Soc* 85:1931–1941 doi:[10.1175/BAMS-85-12-1931](https://doi.org/10.1175/BAMS-85-12-1931)
- Smoyer KE, Rainham DGC, Hewko JN (1999) Integrated analysis of heat-related mortality in the toronto–windsor corridor. Toronto–Niagara Region Study on Atmospheric Change: Report 99–1. Toronto, p.43
- Takahashi K, Honda Y, Emori S (2007) Assessing mortality risk from heat stress due to global warming. *J Risk Res* 10:339–354 doi:[10.1080/13669870701217375](https://doi.org/10.1080/13669870701217375)