

Differential and combined impacts of extreme temperatures and air pollution on human mortality in south–central Canada. Part I: historical analysis

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Abstract This paper forms the first 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 in south–central Canada, focusing on historical analysis (a companion paper—Part II focusing on future estimates). In this study, an automated synoptic weather typing procedure was used to identify weather types that have a marked association with high air pollution levels and temperature extremes, and facilitates assessments of the differential and combined health impacts of extreme temperatures and air pollution. Annual mean elevated mortality (when daily mortality exceeds the baseline) associated with extreme temperatures and acute exposures to air pollution, based on 1954–2000, was 1,082

[95% confidence interval (CI) of 1,017–1,147] for Montreal, 1,047 (CI 994–1,100) for Toronto, 462 (CI 438–486) for Ottawa, and 327 (CI 311–343) for Windsor. Of this annual mean elevated mortality, extreme temperatures are usually associated with roughly 20%, while air pollution is associated with the remaining 80%. Three pollutants (ozone, sulfur dioxide, and nitrogen dioxide) are associated with approximately 75% of total air pollution-related mortality across the study area. The remaining 25% is almost evenly associated with suspended particles and carbon monoxide, the other two pollutants addressed in this study. Of the five pollutants, ozone is most significantly associated with elevated mortality, making up one-third of the total air pollution-related mortality. PM_{2.5} and PM₁₀ were not used as a measure of particulate in the study due to brief data records. The study results also suggest that, on the basis of daily mortality risks, extreme temperature-related weather presents a much greater risk to human health during heat waves and cold spells than air pollution. For example, in Montreal and Toronto, daily mean elevated mortality counts within the hottest weather type were twice as high as those within air pollution-related weather types.

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Introduction

It is well known that air pollution has been strongly linked to human health problems, particularly in vulnerable populations such as the elderly, young children, and those suffering from cardio-respiratory conditions (World Health Organization 2004). For example, Judek et al. (2004)

pointed out that the annual excess number of deaths associated with short-term and long-term exposure to air pollution was estimated to be 1,800 and 4,200, respectively, for eight Census Divisions in Canada with a population of 8.9 million (national total population of 30.0 million in the 2001 Census). Another report released by Toronto Public Health (2004) estimated that about 1,700 premature deaths each year in the City of Toronto (population=2.5 million in the 2001 Census) were associated with acute or short-term exposures to ozone (O_3), nitrogen dioxide (NO_2), carbon monoxide (CO), sulfur dioxide (SO_2), and chronic or long-term exposures to fine particulate matter ($PM_{2.5}$). About 700 of these deaths were attributable to acute exposures alone. The Ontario Medical Association (OMA 2005) estimated that, based on acute exposure to O_3 , SO_2 , NO_2 , CO, and PM, air pollution causes approximately 5,800 premature deaths per year in Ontario (population=11.4 million in the 2001 Census) and almost \$8 billion in direct costs to the provincial health care system.

It is also well known that temperature extremes are responsible for significant numbers of deaths during hot and cold days. For example, a recent study (Medina-Ramón and Schwartz 2007) investigated the relationships between temperature extremes and mortality in 50 US cities, resulting in mortality increases associated to both extreme heat (+5.74%) and extreme cold (+1.59%). In the US, during the hot summer of 1980, an estimated 10,000 deaths were related to oppressive heat (Ross and Lott 2003). The severe 5-day heat wave over the central United States during mid-July 1995 caused 830 deaths, with 525 of these deaths in the City of Chicago (Changnon et al. 1996). During August 2003, western European countries experienced a record-breaking, heat-wave event; in France alone over 14,800 deaths may have been directly caused by this heat wave (Pirard et al. 2005).

Many chronic diseases, especially those of the respiratory and cardiovascular systems, are exacerbated most frequently during or after a period of specific weather conditions (e.g., Kalkstein 1991; Cheng 1991; Nichols et al. 1995; Sheridan and Kalkstein 2004; Shin et al. 2008) and/or high air pollution concentrations (Schwartz et al. 1991; Burnett et al. 1994, 1999; Schwartz 2000, Basu and Ostro 2008). As shown in Table 1 for examples, a number of the previous studies in this field have examined how human-made factors such as atmospheric pollutants affect human health; many others have focused on how natural stressors such as extreme temperatures influence death rates. Some other studies (e.g., Rainham and Smoyer-Tomic 2003; Hu et al. 2008) have investigated associations between extreme temperatures and mortality, considering confounding impacts of air pollutants. However, the differential and combined impacts of extreme temperature-related weather events and high air pollution episodes on human health are

poorly understood. In the light of these concerns, Environment Canada, in partnerships with Toronto Public Health, McMaster University, Health Canada, and Public Health Agency of Canada, has completed a 3-year research project. This project, funded by the Health Policy Research Program, Health Canada, proposed a method based on synoptic weather typing in addition to air pollution levels to evaluate differential and combined impacts of extreme temperatures and air pollution on human mortality in south-central Canada. The results from this study, expressed as elevated mortality (above the baseline) associated with different factors (e.g., heat, cold, pollutants), could be usable by governmental agencies and stakeholders for assisting in developing better policies on health protection and balancing policy decisions. This study may enhance current understanding of environmental problems related to human health in south-central Canada.

The current paper describes the background to the development of an analysis approach to quantitatively estimate elevated mortality, applying an automated synoptic weather typing and mortality baseline analyses. The synoptic weather typing has been adapted to develop a heat-health watch/warning system piloted in Philadelphia, Cincinnati, Rome, Shanghai, and Toronto for the UN Showcase Project (Sheridan and Kalkstein 2004). This method promises to evaluate relationships among a variety of weather elements rather than only individual variables—the synergistic impact of several elements being more significant than the sum of their individual impacts (Kalkstein 1991; Pope and Kalkstein 1996; Kalkstein et al. 1997). Part of the current study focusing on climate change impacts analysis on both future air pollution- and temperature extreme-related mortality in south-central Canada is presented in a companion paper (Part II, Cheng et al. 2009). To effectively estimate climate change-induced future elevated mortality, historical analysis is essential for us to build a solid science foundation on health impacts of air pollution and extreme temperatures. For this study, four cities, Montreal, Ottawa, Toronto, and Windsor, located in south-central Canada, were selected (Fig. 1). There are several reasons for selection of the cities. First, the cities, especially for Windsor, have experienced the hottest weather situation in the country. Second, Toronto and Montreal are the two largest cities, in terms of population, in Canada. Finally, Ottawa is the capital of Canada.

Data sources and treatment

To evaluate differential and combined impacts of air pollution and extreme temperatures on human mortality, meteorological, air pollution, and mortality data are needed. The detailed information, regarding data sources, variables,

Table 1 Examples of previous studies on health impacts of air pollution/extreme temperature

Study	Methodology	Major findings	Study area
Air pollution and human health			
Schwartz et al. 1991	Poisson regression	Acute respiratory illness increases by 27–28% when TSP or NO ₂ levels increase from 10 to 70 µg/m ³	Five cities, Germany
Dockery et al. 1992	Poisson regression	Mortality increase by 16–17% per 100 µg/m ³ increase in PM ₁₀	Two US cities
Stieb et al. 1996	A regression similar to Poisson regression	Asthma emergency visits: 33% higher when daily maximum O ₃ >75 ppb	Saint John, Canada
Burnett et al. 1997	Random effects relative risk regression	O ₃ and respiratory hospitalizations, with relative risks: 1.000–1.088	16 Canadian cities
Burnett et al. 1999	Generalized additive models	Per 10 µg/m ³ increase in PM _{2.5} /PM ₁₀ , the related cardio-respiratory hospitalizations: 3.3%/1.9% more	Toronto, Canada
Goldberg et al. 2003	Generalized linear Poisson regression and natural splines	Daily mortality increases by 4.32%/4.08% due to increase in suspended particles/NO ₂ , across inter-quartile range	Montreal, Canada
Fung et al. 2005	Generalized linear Poisson regression & natural splines	Daily hospitalizations increase by 2.6%/4.0%/5.6% for 1-/2-/3-day mean SO ₂ increase across inter-quartile range	Windsor, Canada
Keatinge & Donaldson 2006	Generalized additive models	Pollutants played little part in excess mortality associated with hot weather	London, UK
Qian et al. 2008	Generalized additive models	Daily mortality increases by 2.20%, 3.28%, 2.35% for non-accidental, cardiovascular, stroke per 10 µg/m ³ increase in PM ₁₀ during hot temperature	Wuhan, China
Shin et al. 2008	Generalized additive Poisson models	Public health risks related to NO ₂ appear to be increasing but the risks for O ₃ is weak	12 Canadian cities
Wong et al. 2008	Poisson regression and natural splines	Excess mortality risk per 10 µg/m ³ related to NO ₂ : 0.90–1.97%, SO ₂ : 0.87–1.61%, PM ₁₀ : 0.26–1.25%, O ₃ : 0.31–0.63%	Four cities in Asia
Extreme temperature and human health			
Kalkstein 1991	Synoptic weather typing	Heat but not pollutants played most part in excess mortality	St. Louis, USA
Kalkstein & Greene 1997	Synoptic weather tying	A very warm summer air mass of maritime origin can increase daily mortality as many as 30 deaths in large eastern US cities	44 US cities
Guest et al. 1999	Threshold temperature: T _{max} >28°C	Annual mean heat-related mortality is 175	Five cities, Australia
Dessai 2002	Non-linear regression	Heat-related mortality is six per 100,000 individuals	Lisbon, Portugal
Davis et al. 2003	Threshold temperature: 16:00 LST heat index >30°C	Heat-related mortality rate per million people was 41.0 in 1960s–1970s, 17.3 in 1980s, 10.5 in 1990s	28 cities, USA
McGregor et al. 2004	Linear regression	Annual ischaemic heart disease mortality peak occurs during the coldest winter seasons	Five counties, UK
Basu & Ostro 2008	Time-stratified case-crossover approach	Cardiovascular mortality increases by 2.6% per 4.7°C increase in mean daily apparent temperature	California, USA
Hu et al. 2008	Time-series classification and regression tree (CART)	Daily mortality increases by 7.3% when T _{max} >32°C and 12.1% when mean SO ₂ exceeds 0.315 ppm	Sydney, Australia
Rocktöv & Forsberg 2008	Generalized additive Poisson models	Daily mortality increases by 3.1–7.7% during heat waves	Stockholm, Sweden

Fig. 1 Location map of the four selected cities



and record length, is described in Table 2. In this study, hourly surface meteorological data for the period 1954–2000 were used for the treatment of missing data. Missing data of each meteorological variable were interpolated using a temporal linear method in cases where the data were missing for three consecutive hours or less; days with data missing for four or more consecutive hours were excluded from the analysis. Of the total dataset, about 1% of the total days required missing data interpolation; after interpolation, the dataset was over 99.7% complete. Additionally, only six-hourly weather variables observed

at 03:00, 09:00, 15:00, and 21:00 local standard time (LST) were used in the study. For air pollution data, several monitoring sites listed in Table 2, based on the length and completeness of the available data records, were chosen to calculate hourly/daily mean concentrations representing average air pollution conditions for each of the selected cities (refer to Cheng et al. 2007a for details on air pollution data treatment).

To effectively evaluate extreme temperature- and air pollution-related health risks, the daily aggregated non-traumatic mortality data have to be treated to remove inter-

Table 2 Data used in the study

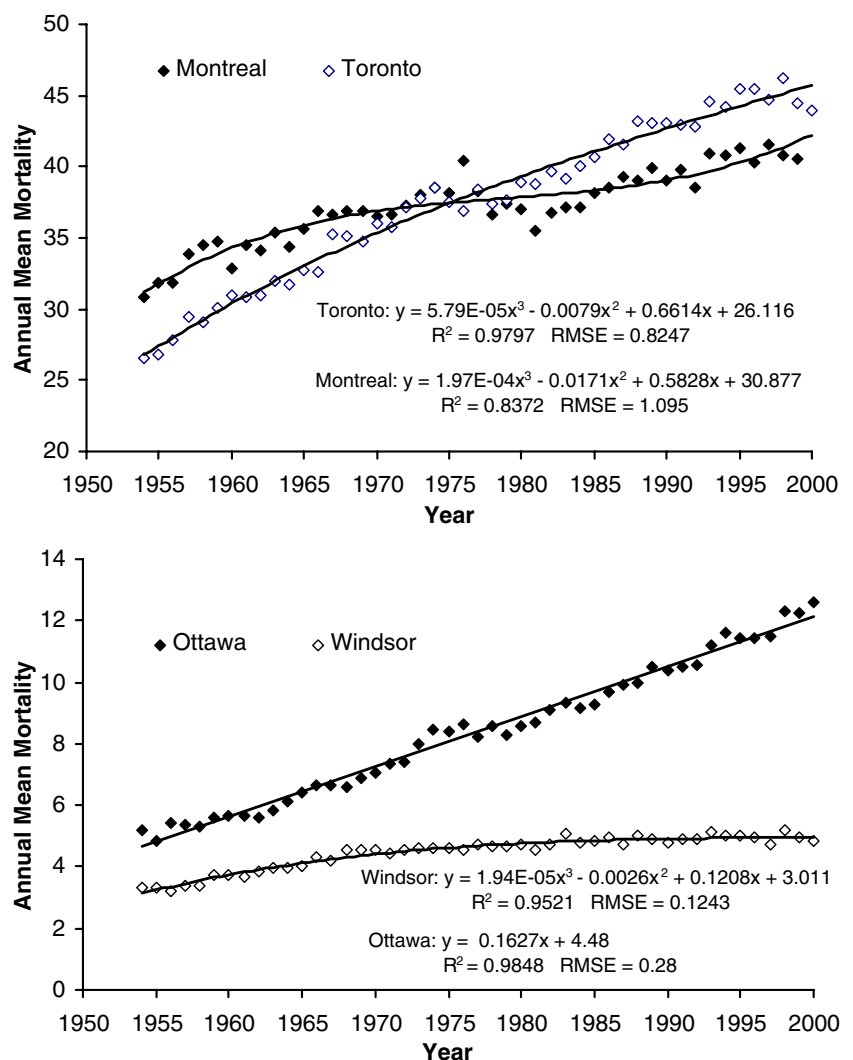
Description	Variable	Source	City
Total non-traumatic mortality (1954–2000):			
ICD-6 (1953–1957): 001–795	Daily aggregated mortality counts	Statistics Canada	Montreal (Island)
ICD-7 (1958–1968): 001–795			Ottawa
ICD-8 (1969–1978): 000–796			Toronto (Metropolitan)
ICD-9 (1979–1999): 001–799			Windsor
ICD-10 (2000): A00–R99			
Six-hourly surface meteorological observations at 03:00, 09:00, 15:00, 21:00 local standard time (1954–2000)	Air temperature (°C) Dew point (°C) Sea-level air pressure (hPa) Total cloud cover (tenths) U-wind and V-wind (m s^{-1})	Environment Canada's National Climate Data and Information Archive	International airports in Montreal, Ottawa, Toronto, and Windsor
Hourly/daily air pollution observations:			
1980–2000 for ozone	Carbon monoxide (CO)	Environment Canada's National Air Pollution Surveillance (NAPS) network	Monitoring stations: Montreal: 7 Ottawa: 1 Toronto: 3 Windsor: 2
1974–1996 for suspended particles	Nitrogen dioxide (NO ₂)		
1974–2000 for rest of pollutants	Ozone (O ₃)		
	Sulfur dioxide (SO ₂)		
	Suspended particles (SP)		

annual trends and seasonal fluctuations. The inter-annual trends over time for total non-traumatic mortality are shown in Fig. 2. These upward trends likely resulted from several factors, including increases in total population and changes in population age structure (Kalkstein et al. 1997). Other factors (i.e., improvements to health care and economic/living conditions) could reduce the upward trends. Since this study attempts to analyze health impacts of extreme temperatures and air pollution, such non-environmental factors, representing confounding influences within the mortality data, should be removed. The mortality upward trends over time can be removed by fitting a polynomial regression line through annual mean mortality counts against time (in years), which is the baseline I shown in Fig. 2. It is noteworthy that the upward trend pattern for Montreal is different from that of other cities; this is a result of a decline in population (about 0.2 million) from 1971 to 1981, based on the census data of Statistics Canada. The residual or difference between each day’s actual mortality count and the baseline count (Fig. 2) indicates that upward

trends due to non-environmental factors have been removed. From removing non-environmental factors using the baseline I, some health impacts of extreme temperatures and air pollution were also removed since the extreme hot and polluted days were included in construction of the baseline I. The next step is to modify the baseline I to develop the baseline II using only weather types associated with relatively good air quality and comfortable weather conditions (see the section ‘Results and discussion’ for a detailed information).

In addition to inter-annual trends, the mortality seasonal fluctuations need to be removed from the analysis. Using monthly mortality baseline II, seasonal fluctuations can be excluded from mortality data by removing monthly inter-annual trends. The monthly mortality baseline II was developed by fitting monthly polynomial regression models, which usually explain over 80% of the data variances for the four selected cities. In addition to inter-annual and seasonal fluctuations of mortality, consideration was given to removing weekly fluctuations of mortality from the data.

Fig. 2 Inter-annual total non-traumatic mortality trends (baseline I). The x described in equations is set as 1 for the year 1954, 2 for 1955, and so on



However, the weekly fluctuations within a weather group were not statistically significant for the four selected cities and therefore were not considered to be removed.

Analysis techniques

To analyze differential and combined impacts of extreme temperatures and air pollution on human health, three major methods or steps are used in the study. First, an automated synoptic weather typing was employed to classify each day of the dataset into a distinctive weather type based on weather characteristics represented by a variety of weather variables. Second, daily air pollution data were used to identify the weather types most highly associated with high air pollution levels for each of the pollutants. Finally, temperature extreme- and air pollution-related mortality could be distinguished by linking daily elevated mortality (above the baseline) with hot/cold/air pollution-related synoptic weather types. The detailed information on analysis techniques is summarized in Fig. 3.

Synoptic weather typing

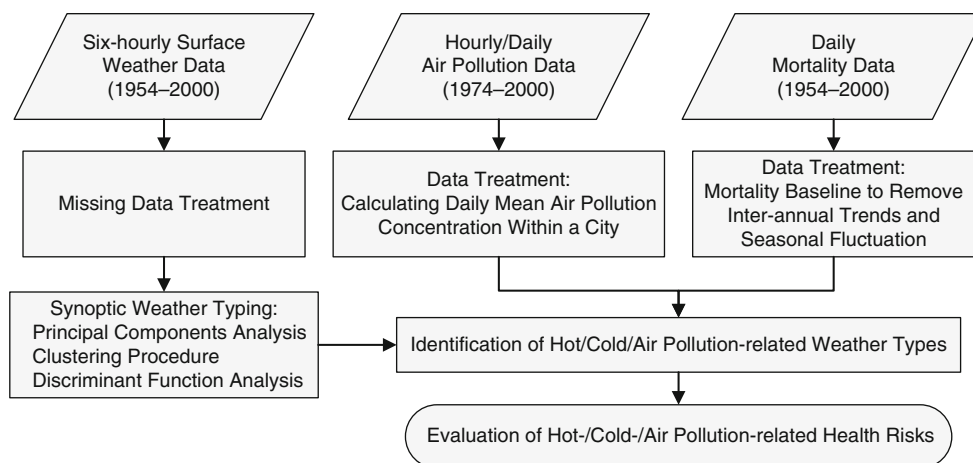
An automated synoptic weather typing, based primarily on air mass similarity and differentiation within and between weather types, was used to assign each day of the dataset to a distinctive weather type. The entire suite of 24 weather variables, including six-hourly surface weather observations of air temperature, dew point temperature, sea-level air pressure, total cloud cover, and south–north and west–east winds, were used in synoptic weather typing. As part of this research, Cheng et al. (2007a, 2007b) have developed weather typing procedures for evaluation of climate change impacts on air pollution concentrations for the selected four cities, which were also used in this study. Due to space limitation, weather typing procedures are briefly summarized here. Weather typing procedures are

comprised of a two-step process: (1) daily synoptic weather types were categorized using principal components analysis (PCA) and a hierarchical agglomerative cluster method—an average linkage clustering procedure, and (2) all days in the dataset were regrouped by a non-hierarchical method—discriminant function analysis using the centroids of the hierarchical weather types as seeds. First, a hierarchical agglomerative clustering procedure was suitable for the initial classification since the number of weather types was not predetermined (Davis 1986; Kalkstein et al. 1996; Cheng and Kalkstein 1997; Cheng and Lam 2000). The correlation matrix-based PCA (Jolliffe 1986; Applequist et al. 2002) was performed to reduce the 24 inter-correlated weather variables into seven linearly independent components, explaining much of the variance (i.e., 88–92% across the cities) within the original dataset. Days with similar meteorological conditions tended to exhibit similar component scores. The average linkage clustering procedure generated statistical diagnostics to produce an appropriate number of clusters. The diagnostics attempts to minimize the within-cluster variances and to maximize the between-cluster variances (Boyce 1996; Cheng and Lam 2000; Cheng et al. 2007a). Second, following the hierarchical classification, a non-hierarchical classification procedure was used to reclassify all days within the dataset. Improvement in the cluster structure resulting from non-hierarchical reclassification was evaluated by comparing within-/between-cluster variances. Cheng et al. (2007a) have concluded that the reclassification results were better than the original, with smaller within-cluster variances and larger between-cluster variances, which is consistent with that of previous studies (e.g., DeGaetano 1996).

Link between weather types and air quality

Following weather type classification, daily mean and maximum air pollution concentrations were used to identify the synoptic weather types most highly associated with high

Fig. 3 Flow chart of methodologies and steps used in the study



air pollution concentrations for each of the selected pollutants. As shown in Table 3, two measurements, within-weather-type mean air pollution concentrations and frequency of high air pollution episodes, were used to determine relationships between weather types and air quality. Daily mean air pollution concentrations for each type were then determined to ascertain whether the air pollution levels within the particular weather types were distinctively high or low. In addition, a ratio of the within-weather-type occurrence of high air pollution episodes (actual frequency) to the occurrence of the weather type in the entire record (expected frequency) was utilized to

determine whether any of the weather types were over-represented for high air pollution episodes. Weather types with ratios significantly greater than 1.0 clearly had a greater proportion of days with high air pollution episodes than would be expected. If the frequency ratio was greater than 1.0 and the within-weather-type mean concentration was higher than the overall mean, that weather type was selected as an air pollution-related weather type. As shown in Table 3 for Toronto, nine weather types were defined as the O₃-related types. A χ^2 test was used to ascertain whether the actual frequencies of high air pollution events (daily air pollution concentration with one, two, and three

Table 3 Within-weather-type O₃ level by concentration anomalies (overall mean=17.0 ppb) for nine O₃-related weather types (types 1–9) and examples of nine low-O₃-level types (types 17–25) in Toronto (1980–2000)

Synoptic type			O ₃ concentration level									
Type	Days	Freq. (%) ¹ (a)	Mean ² (ppb)	1 std. dev. above mean			2 std. dev. above mean			3 std. dev. above mean		
				Days	Freq. (%) ³ (b)	Ratio ⁴ (b)/(a)	Days	Freq. (%) ³ (c)	Ratio ⁴ (c)/(a)	Days	Freq. (%) ³ (d)	Ratio ⁴ (d)/(a)
1	173	2.26	32.02	130	11.76	5.21	74	18.78	8.31	21	19.09	8.45
2	223	2.91	26.14	136	12.31	4.23	62	15.74	5.40	23	20.91	7.18
3	260	3.40	28.47	186	16.83	4.96	83	21.07	6.20	23	20.91	6.16
4	233	3.04	19.77	115	10.41	3.42	45	11.42	3.75	12	10.91	3.59
5	161	2.10	21.87	88	7.96	3.79	37	9.39	4.47	12	10.91	5.19
6	107	1.40	15.94	40	3.62	2.59	12	3.05	2.18	5	4.55	3.25
7	81	1.06	15.30	35	3.17	2.99	8	2.03	1.92	1	0.91	0.86
8	348	4.54	5.19	64	5.79	1.27	12	3.05	0.67	1	0.91	0.20
9	285	3.72	8.36	64	5.79	1.56	13	3.30	0.89	1	0.91	0.24
17	270	3.53	-13.68	0	0.00	0.00	0	0.00	0.00	0	0.00	0.00
18	235	3.07	-11.72	0	0.00	0.00	0	0.00	0.00	0	0.00	0.00
19	125	1.63	-11.54	1	0.09	0.06	0	0.00	0.00	0	0.00	0.00
20	138	1.80	-15.99	1	0.09	0.05	0	0.00	0.00	0	0.00	0.00
21	70	0.91	-11.29	0	0.00	0.00	0	0.00	0.00	0	0.00	0.00
22	304	3.97	-15.70	1	0.09	0.02	0	0.00	0.00	0	0.00	0.00
23	110	1.44	-9.95	0	0.00	0.00	0	0.00	0.00	0	0.00	0.00
24	203	2.65	-16.80	2	0.18	0.07	0	0.00	0.00	0	0.00	0.00
25	174	2.27	-11.04	0	0.00	0.00	0	0.00	0.00	0	0.00	0.00
Sub-total ⁵	2,114	27.61	18.31	973	88.05	3.19	385	97.72	3.53	110	100	3.62
Total ⁶	7,655			1,105			394			110		

¹ Percentage occurrence of the weather type or expected frequency for high O₃-level events (within-weather-type number of days divided by the number of total days)

² Within-weather-type daily mean anomalies of O₃ concentrations (overall mean=17.0 ppb)

³ Percentage occurrence (actual frequency) of the days with one, two, and three standard deviations above the overall mean (17.0 ppb) within a particular weather type (within-weather-type number of the events divided by the number of total events)

⁴ Ratio of actual frequency of the high O₃-level events over the expected frequency. A ratio greater than one indicates that a larger proportion of days in the weather type possess higher O₃ levels than would be expected

⁵ The sum of the nine O₃-related weather types and some small weather types that are most associated with high O₃ concentration levels, but not shown in Table 4

⁶ The sum of all weather types

standard deviations above the overall mean) were significantly different from their expected occurrences (χ^2 test significance level of 0.001). This method was then applied to different pollutants for each of the selected cities.

Health impacts of extreme temperatures and air pollution

Synoptic weather typing can be used to evaluate the differential and combined impacts of extreme temperatures and air pollution on elevated mortality. In this study, the elevated mortality counts within the weather types associated with high air pollution concentrations—but with comfortable weather conditions—are treated as the impacts of air pollution on human health. The impacts of extreme temperatures on human health might be determined by the hot and cold weather types. Although the hot/cold weather groups are usually associated with high air pollution concentrations, elevated mortality within the hot/cold groups was defined as extreme temperature-related mortality since extreme temperatures are most relevant to elevated mortality in these weather groups (refer to the section ‘Results and discussion’ for a more detailed information).

The synoptic weather typing procedure can be used to analyze differential impacts of air pollutants on elevated mortality counts as well. The air pollution-related weather types may be associated with high air pollution concentrations for one single pollutant or multiple pollutants. For the former case, within-weather-type elevated mortality can be identified as associated with that particular pollutant. For the latter case, the study assumes that within-weather-type elevated mortality is associated with the one particular pollutant that is most important to the weather type (refer to the section ‘Results and discussion’ for a more detailed information).

Consideration was given to taking into account lag times of extreme temperature and air pollution impacts on mortality. Based on the analysis, no-lag-time relationships between heat and mortality are more significant than other lag times across the study area. This is consistent with the previous studies (e.g., Dessai 2002; Rainham and Smoyer-Tomic 2003; Sheridan and Kalkstein 2004). As a result, the within-weather-type elevated mortality was estimated in the study based on lag-zero-day relationships.

Results and discussion

Findings derived from this study are significant in three areas: (1) extreme temperature- and air pollution-related weather types, (2) mortality baseline, and (3) differential and combined health impacts of temperature extremes and air pollution. The major findings in each of the areas are discussed in this section as follows.

Extreme temperature- and air pollution-related weather types

The number of major synoptic weather types (with sizes above 1% of the total days) identified for the selected cities varied slightly from one city to another: 39, 37, 36, and 39 for Montreal, Ottawa, Toronto, and Windsor, respectively. The smaller weather types were still included in the analysis. As part of this study, Cheng et al. (2007a) have determined extreme temperature- and air pollution-related weather types for the selected cities. For each of the four selected cities, there are three hot weather types, four or five cold weather types, and the number of air pollution-related weather types, as shown in Table 4 for Toronto (similar results were discovered for the other cities as well, but not shown). The three hot weather types (Hot1, Hot2, and Hot3) can capture 50–60%, 20–30%, and about 10% of the total days with 15:00 LST temperature $\geq 32^\circ\text{C}$, respectively, across the study area. For determination of the cold weather types, the criterion varies from location to location, based on the difference of January mean 15:00 temperature among the cities. The within-weather-type mean 15:00 temperature of $\leq -6^\circ\text{C}$ was used to define a cold weather type for Ottawa and Montreal, and of $\leq -3^\circ\text{C}$ for Toronto and Windsor.

As described in the previous section, air pollution-related weather types were defined based on (1) within-weather-type daily mean concentrations and (2) the ratios of actual frequency of high pollution level events over the expected frequency. The within-weather-type mean concentrations and ratios for nine O_3 -related weather types and nine low- O_3 -level types in Toronto are shown in Table 3, as an example. The similar results were found for other selected cities but not shown due to limitations of space. As shown in Table 3, daily mean anomalies of O_3 concentration within weather types 1–9 are much higher than the overall mean (17.0 ppb in Toronto). Most of other weather types (e.g., weather types 17–25) possess negative mean anomalies of O_3 concentrations. For weather type 1 in Toronto, the expected frequency of high air pollution events would be 2.26%, based on the size of the weather type. However, the actual frequency of the high air pollution events with one and three standard deviations above the overall mean was about 12% and 19%, respectively—more than five and eight times what might otherwise be expected. Through these analyses, ten, nine, nine, and nine O_3 -related weather types were identified for Montreal, Ottawa, Toronto, and Windsor, respectively, of which the first three are also called hot weather types. On average across the four selected cities, these weather types accounted for 83% and 97% of the total high O_3 events with greater than one and three standard deviations above the overall mean, respectively.

Table 4 Ten weather groups in Toronto: three hot, one cold, five air pollutant-related, and one “other”

Type	15:00 LST temperature (std. dev.)		15:00 LST dew point (std. dev.)		15:00 LST wind speed/direction		Pollutants associated with weather types					Weather groups
1	29.82	(2.73)	17.37	(3.21)	5.63	WSW	O ₃		NO ₂	SP		Hot1/AP
2	27.23	(3.11)	16.44	(3.42)	6.31	WSW	O ₃	SO ₂	NO ₂	SP		Hot2/AP
3	26.78	(2.63)	14.35	(3.38)	5.05	S	O ₃	SO ₂	NO ₂	SP		Hot3/AP
4	24.58	(3.04)	18.49	(2.16)	3.95	S	O ₃		NO ₂	SP		AP-O ₃
5	24.45	(3.04)	15.14	(3.39)	4.58	S	O ₃	SO ₂	NO ₂	SP	CO	AP-O ₃
6	23.04	(2.91)	9.45	(3.74)	4.53	SSE	O ₃		NO ₂	SP	CO	AP-O ₃
7	25.03	(2.35)	13.26	(2.97)	3.30	SE	O ₃					AP-O ₃
8	19.31	(3.27)	11.99	(3.22)	3.78	ESE	O ₃		NO ₂			AP-O ₃
9	21.03	(3.14)	7.64	(3.65)	4.08	SSE	O ₃		NO ₂		CO	AP-O ₃
10	16.64	(3.60)	11.95	(3.47)	4.25	SE			NO ₂			AP-NO ₂
11	13.17	(3.74)	3.74	(3.52)	4.13	SE			NO ₂		CO	AP-NO ₂
12	0.92	(3.03)	-3.46	(2.87)	5.90	W		SO ₂				AP-SO ₂
13	8.73	(4.61)	0.63	(3.61)	5.27	W		SO ₂	NO ₂	SP	CO	AP-SP
14	3.63	(3.55)	-0.10	(3.14)	6.32	WSW		SO ₂		SP	CO	AP-SO ₂
15	2.55	(4.75)	-1.74	(4.14)	8.51	WSW		SO ₂				AP-SO ₂
16	5.32	(3.90)	0.46	(3.59)	3.27	SE		SO ₂	NO ₂	SP	CO	AP-NO ₂
17	7.71	(3.76)	4.23	(3.43)	3.78	SSE		SO ₂	NO ₂	SP	CO	AP-SP
18	-2.48	(2.96)	-5.67	(3.12)	5.22	ENE		SO ₂				AP-SO ₂
19	16.23	(4.10)	10.53	(3.65)	5.54	SW		SO ₂	NO ₂	SP	CO	AP-SP
20	12.75	(5.65)	2.96	(5.25)	4.27	SSE					CO	AP-CO
21	-1.10	(4.38)	-8.29	(3.42)	5.27	NNW					CO	AP-CO
22	-2.87	(3.23)	-8.03	(3.30)	3.81	SSW		SO ₂	NO ₂	SP	CO	AP-SO ₂
23	-5.25	(3.39)	-9.64	(3.67)	6.76	NNW						Cold
24	-10.44	(3.55)	-14.66	(3.83)	4.81	N		SO ₂	NO ₂	SP	CO	Cold/AP
25	-9.77	(4.39)	-16.03	(4.20)	4.06	NNW		SO ₂	NO ₂		CO	Cold/AP
26	-7.07	(3.55)	-12.15	(3.71)	7.93	W		SO ₂				Cold/AP
27	-2.97	(3.98)	-7.60	(3.95)	5.16	SW		SO ₂		SP	CO	Cold/AP
28	20.66	(3.33)	8.76	(3.50)	6.72	WNW						Other
29	23.01	(3.68)	15.38	(3.00)	6.04	WNW						Other
30	21.13	(3.09)	8.76	(3.14)	5.68	NNW						Other
31	11.75	(4.03)	-1.55	(3.67)	5.34	NW						Other
32	7.79	(4.13)	-0.51	(3.87)	7.29	WNW						Other
33	3.37	(3.64)	-1.97	(3.15)	5.28	NNW						Other
34	2.71	(3.80)	0.42	(3.68)	6.55	E						Other
35	2.39	(4.17)	0.44	(4.22)	5.23	N						Other
36	-2.22	(4.38)	-6.64	(4.39)	9.53	WNW						Other

Similar analyses were also applied to the remainder of the pollutants for each of the selected cities. The summarized results of the weather types highly associated with each of the pollutants are shown in Table 4 (using Toronto as an example). Some weather types showed significant linkage with high air pollution concentrations for many pollutants (up to five); other types possessed good air quality and were not significantly related to any pollutant. If a weather type was associated with high air pollution levels for more than one pollutant, it was important to determine which air pollutant was most significantly

associated with the weather type, based on the highest weather-type-frequency ratio described in the section (*‘Analysis techniques’*) above. For example, 16 weather types are associated with relative high SO₂ levels in Toronto; however, only five of them are most significantly related to SO₂, while for the rest of the weather types, other pollutants are more important. As shown in Table 4, weather types for this study were divided into ten groups: three hot weather-related (including air pollution) groups (Hot1/AP, Hot2/AP, Hot3/AP), one cold weather-related (including air pollution) group (Cold/AP), five air

pollutant-related groups (CO, NO₂, O₃, SO₂, SP), and one “other” group with relatively good air quality and comfortable weather conditions. For each of the four cities being studied, the percentage occurrences of the ten weather groups are fairly consistent across the study area, with only a small variation (Fig. 4). Such weather grouping can facilitate the analysis of differential and combined impacts of extreme temperatures and air pollution on human mortality.

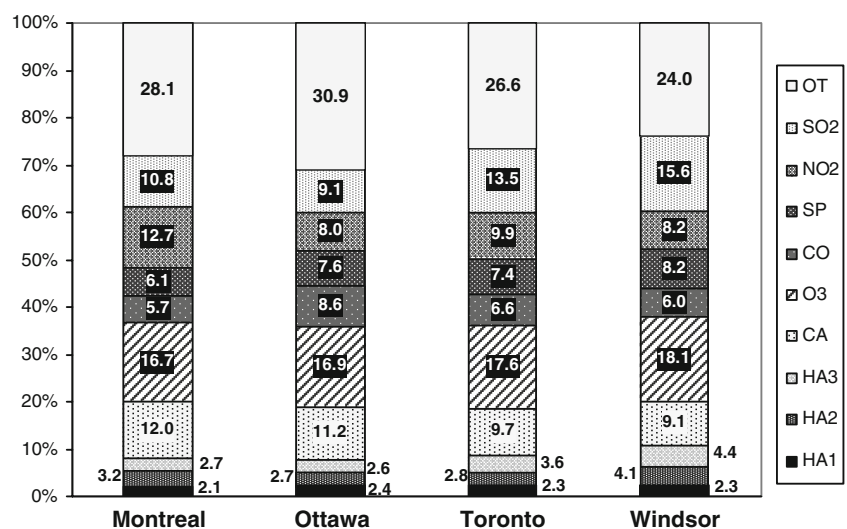
Mortality baseline

The inter-annual upward trends over time for total non-traumatic mortality (mortality baseline I) shown in Fig. 2 were removed to minimize confounding influences of non-environmental factors (e.g., increases in total population and changes in population age structure). However, to quantitatively assess elevated mortality (above the baseline) associated with extreme temperatures and air quality, the mortality baseline I needs to be modified. Following determination of the ten weather groups, mortality baseline I can be adjusted to develop baseline II using only the “other” weather group. In fact, some low-frequency weather types not shown in Table 4, which were identified as “other,” were also included in the development of baseline II. Baseline II was developed by calculating the within-“other”-weather-group mean mortality from anomalous data against baseline I for each 3-month season (December–February, March–May, June–August, September–November). As shown in Fig. 5 for Toronto as an example (similar results were discovered in other cities), baseline II was lower than baseline I since baseline I includes all days (including hot/cold/high air pollution episodes) in its construction. The difference between two baselines that represents part of the extreme temperatures and air pollution effects, which was removed from baseline I, should be added back to the elevated

mortality. As a result, the baseline II can represent normal or natural deaths without the effects of extreme temperatures and air pollution. A positive mortality residual (above baseline II) should represent the elevated mortality associated with extreme temperatures and air pollution. A negative mortality residual (below baseline II) indicates a situation with no elevated mortality relative to extreme temperatures and air pollution. When within-weather-type annual and daily mean elevated mortalities were calculated, the daily negative mortality residual was set as zero.

The advantage of using the mortality baseline, as derived for the current study, is its enhancement of the relationship between extreme temperatures/air pollution and mortality. It could also minimize the confounding impacts of non-environmental factors such as population increase and improvements to health care and living/economic conditions. In the health studies, mortality rates were often used to remove the impacts of population growth. When long-term health data (e.g., ten-year spans of data records or more) are considered, it is insufficient to remove only population effects from mortality data so as to analyze health impacts of air pollution and extreme temperatures. To demonstrate this, population census data were used and tested to calculate mortality rates for the selected four cities. To effectively remove impacts of population increase and changes in population age structure, an elderly population (≥ 65 years) was used. According to the results, there appears to be a significant downward trend in mortality rates for each of the cities, due to improvements to health care and living/economic conditions (e.g., use of air conditioning). On average, across the selected four cities, daily mean mortality rates per 100,000 elderly people were about 30 in the early 1950s, dropping to 15 by the year 2000. For reliable, long-term, time-series health data, this downward trend should also be removed in order to prevent these non-environmental factors from influencing results.

Fig. 4 Percentage occurrence of the ten weather groups in the four cities (*HA1*, *HA2*, and *HA3* represent the three hot weather groups; *CA* is the cold weather group; *O₃*, *NO₂*, *SO₂*, *CO*, and *SP* are different pollutant-related weather groups; and *OT* is the “other” or comfortable weather group)



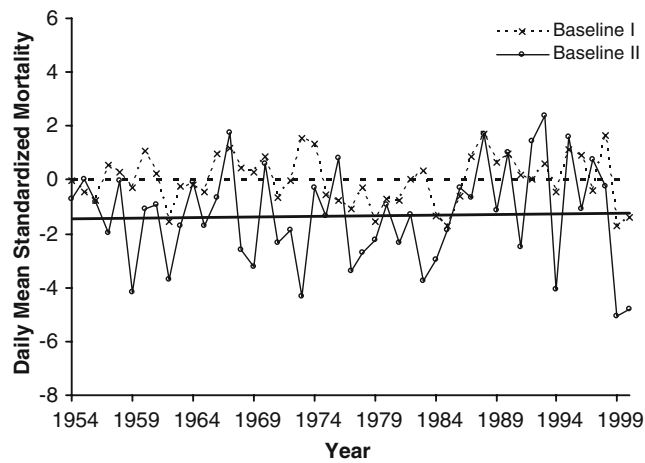


Fig. 5 Sample of mortality baselines I and II for summer season (June–August) in Toronto

Health impacts of temperature extremes and air pollution

Figure 6 shows quantitatively summarized results of the differential and combined impacts of extreme temperatures and air pollution on elevated non-traumatic mortality for the four selected cities. A mean annual total elevated mortality was calculated from the sum of positive mortality residuals for all days within each of the ten weather groups, divided by the total number of years. Generally, the proportion of elevated mortality associated with extreme temperatures and air pollution was consistent across the study area. Extreme temperatures were usually associated with over 20% of mean annual total elevated mortality; air pollution was related to the remaining 80%. Of air pollution-related

mortality, three pollutants (O_3 , SO_2 , and NO_2) were associated with about 75% across the study area. The remaining 25% was almost evenly associated with SP and CO, the other two pollutants used in the study. Of the five pollutants, O_3 was the most highly associated with elevated mortality in each of the cities, responsible for one-third of the total air pollution-related mortality.

Although “other” weather group is usually associated with relatively good air quality and comfortable weather conditions, there still exists some degree of within-type variance. The elevated mortality within the “other” weather group was still found to be associated with air pollution. To demonstrate this, days within the “other” weather group were divided into air pollution concentration deciles for each pollutant; the daily mean mortality was then calculated for each of the deciles. The results of the decile evaluation indicated that in the “other” weather group, there were significant relationships between air pollution concentrations and elevated mortality counts across the study area. Within-decile mean mortality residuals in the bottom deciles were usually lower than those of the top deciles for all pollutants except for CO. In addition to this decile analysis, within-“other”-weather-group regression results also show that only air pollutants other than weather variables are significantly associated with elevated mortality, with a model R^2 of 0.71, 0.62, 0.40, and 0.30 for Montreal, Ottawa, Windsor and Toronto, respectively (refer to a companion paper—Part II, Cheng et al. 2009 for details on regression). This finding is consistent with that of previous studies (Lambert et al. 1998; Toronto Public Health 2001; Vedal et al. 2003), which concluded that

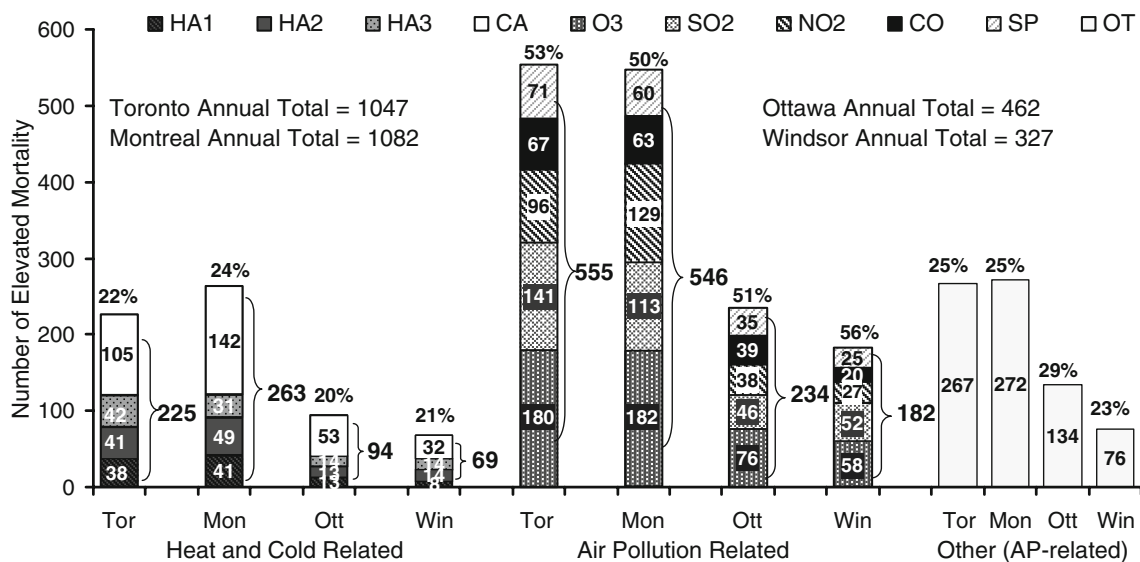


Fig. 6 Mean annual total elevated non-traumatic mortality caused by heat/cold and air pollutants in four cities (1954–2000). HA1, HA2, and HA3 represent three hot weather groups; CA is the cold weather group; O_3 , NO_2 , SO_2 , CO, and SP are different air pollutant-related weather

groups; and OT is the “other” weather group. Tor, Mon, Ott, and Win represent the four cities: Toronto, Montreal, Ottawa, and Windsor. Legend “left-to-right” is equivalent to bars “bottom-to-top”

there is no evidence of clear thresholds of pollutant concentrations associated with increased elevated mortality.

In addition to annual total elevated mortality counts, the daily mean elevated mortality breakdown by the ten weather groups was examined for the four cities. As Fig. 7 illustrates, daily mean elevated mortality was much higher for the extreme temperature-related weather groups than it was for either the air pollution-related or “other” weather groups, especially in Montreal and Toronto. In these two larger cities, daily mean elevated mortality counts within the extreme hot weather group were twice as high as those within “other” weather group. The smaller difference between daily elevated mortalities associated with extreme temperatures and air pollution in Ottawa and Windsor might be due to the small number of daily mortality counts. To more effectively analyze health impacts of extreme temperatures and air pollution for the smaller cities, more research should be conducted using a larger daily sample size of health outcomes, such as hospital admissions and emergency room visits.

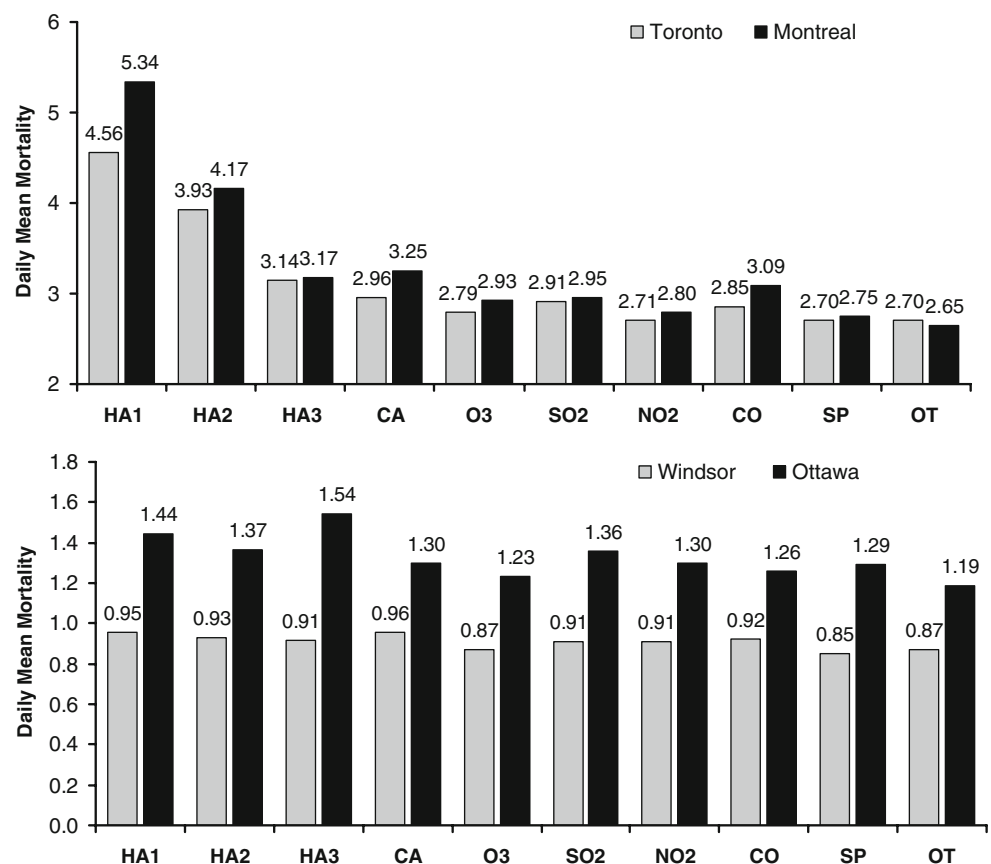
Conclusions

A major goal of this study has been to analyze the differential and combined impacts of extreme temperatures

and air pollution on human mortality for four selected cities (Montreal, Ottawa, Toronto, and Windsor) in south-central Canada. The major findings from this study were summarized as follows:

- The annual average number of elevated mortality attributable to extreme temperatures and acute exposure to air pollution, based on 1954–2000, was 1,082 [95% confidence interval (CI) of 1,017–1,147] for Montreal, 1,047 (CI 994–1,100) for Toronto, 462 (CI 438–486) for Ottawa, and 327 (CI 311–343) for Windsor.
- Of this elevated mortality, extreme temperatures were usually associated with over 20% across the study area; air pollution was related to the remaining 80%.
- Of air pollution-related elevated mortality, three pollutants (O_3 , SO_2 , and NO_2) were associated with about 75% across the study area. The remaining 25% was almost evenly associated with SP and CO, the other two pollutants included in the study. Of the five pollutants, O_3 was most highly associated with elevated mortality in each of the cities, accounting for one-third of total air pollution-related mortality.
- Daily mean heat-related mortality was much higher than that associated with air pollution-related and other weather groups, especially in Montreal and Toronto. Daily mean elevated mortality within the extreme hot

Fig. 7 Daily mean elevated mortality breakdown by weather groups: the *top panel* for Toronto and Montreal and the *bottom panel* for Windsor and Ottawa (1954–2000). HA1, HA2, and HA3 represent three hot weather groups; CA is the cold weather group; O_3 , NO_2 , SO_2 , CO , and SP are different air pollutant-related weather groups; and OT is the “other” weather group



weather group in Montreal (5.3; CI 4.7–5.9) and Toronto (4.6; CI 4.1–5.1) was twice as high as that associated with “other” weather group (2.7; CI 2.5–2.9).

A general conclusion from this study is that a combination of synoptic weather typing and mortality baseline approaches can be useful to distinguish health impacts of temperature extremes and air pollution concentrations. This study aims to provide decision makers with scientific information needed for public policy risk identification and assessment. The results of this study, expressed as elevated mortality above the baseline associated with various factors (e.g., heat, cold, pollutants), can be used by governmental agencies and stakeholders to help them develop better policies on health protection and to balance policy decisions. The study could enhance our understanding of environmental problems related to human health. To support the recommendation of adaptation policies to reduce risks to vulnerable populations due to climate change, it is necessary to estimate possible changes in future extreme temperature- and air pollution-related mortality, which is the major objective of a companion paper (Part II, Cheng et al. 2009).

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References

- Applequist S, Gahrs GE, Pfeffer RL, Niu XF (2002) Comparison of methodologies for probabilistic quantitative precipitation forecasting. *Weather Forecast* 17:783–799. doi:10.1175/1520-0434(2002)017<0783:COMFPQ>2.0.CO;2
- Basu R, Ostro BD (2008) A multicounty analysis identifying the populations vulnerable to mortality associated with high ambient temperature in California. *Am J Epidemiol* 168:632–637. doi:10.1093/aje/kwn170
- Boyce AJ (1996) Mapping diversity: a comparative study of some numerical methods. In: Cole AJ (ed) *Numerical taxonomy*. Academic, New York, pp 1–30
- Burnett RT, Bartlett S, Krewski D, Roberts G, Raad-Young M (1994) Air pollution effects on hospital admissions: a statistical analysis of parallel time series. *Environ Ecol Stat* 1:325–332. doi:10.1007/BF00469429
- Burnett RT, Brook JR, Yung WT, Dales RE, Krewski D (1997) Association between ozone and hospitalization for respiratory diseases in 16 Canadian cities. *Environ Res* 72:24–31. doi:10.1006/enrs.1996.3685
- Burnett RT, Smith-Doiron M, Stieb D, Cakmak S, Brook J (1999) Effects of particulate and gaseous air pollution on cardiorespiratory hospitalizations. *Arch Environ Health* 54:130–139
- Changnon SA, Kunkel KE, Reinke BC (1996) Impacts and responses to the 1995 heat wave: a call to action. *Bull Am Meteorol Soc* 77:1497–1506. doi:10.1175/1520-0477(1996)077<1497:IARTTH>2.0.CO;2
- Cheng CS (1991) Synoptic climatological categorization and human mortality in Shanghai, China. *Proc Middle S Div Assoc Am Geogr* 24:5–11
- 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, 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 II: future estimates. *Air Qual Atmos Health* doi:10.1007/s11869-009-0026-2
- Cheng CS, Kalkstein LS (1997) Determination of climatological seasons for the East Coast of the U.S. using an air mass-based classification. *Clim Res* 8:107–116. doi:10.3354/cr008107
- Cheng CS, Lam KC (2000) Synoptic typing and its application to the assessment of climatic impact on concentrations of sulfur dioxide and nitrogen oxides in Hong Kong. *Atmos Environ* 34:585–594. doi:10.1016/S1352-2310(99)00194-6
- Davis JC (1986) *Statistics and data analysis in geology*, 2nd edn. Wiley, New York, p 646
- Davis RE, Knappenberger PC, Michaels PJ, Novicoff WM (2003) Changing heat-related mortality in the United States. *Environ Health Perspect* 111:1712–1718
- DeGaetano A (1996) Delineation of mesoscale climate zones in the northeastern United States using a novel approach to cluster analysis. *J Clim* 9:1765–1782. doi:10.1175/1520-0442(1996)009<1765:DOMCZI>2.0.CO;2
- 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
- Dockery DW, Schwartz J, Spengler JD (1992) Air pollution and daily mortality: association with particulates and acid aerosols. *Environ Res* 59:362–373. doi:10.1016/S0013-9351(05)80042-8
- Fung KY, Luginaah I, Gorey KM, Webster G (2005) Air pollution and daily hospital admissions for cardiovascular diseases in Windsor, Ontario. *Can J Public Health* 96:29–33
- Goldberg MS, Burnett RT, Valois MF, Flegel K, Bailar JC III, Brook J, Vincent R, Radon K (2003) Associations between ambient air pollution and daily mortality among persons with congestive heart failure. *Environ Res* 91:8–20. doi:10.1016/S0013-9351(02)00022-1
- Guest CS, Willson K, Woodward AJ, Hennessy K, Kalkstein LS, Skinner C, McMichael 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. doi:10.3354/cr013001
- Hu W, Mengersen K, McMichael A, Tong S (2008) Temperature, air pollution and total mortality during summers in Sydney, 1994–2004. *Int J Biometeorol* 52:689–696. doi:10.1007/s00484-008-0161-8

- Jolliffe IT (1986) Principal component analysis. Springer, New York, p 271
- Judek S, Jessiman B, Stieb D, Vet R (2004) Estimated number of excess deaths in Canada due to air pollution. http://www.hc-sc.gc.ca/ahc-asc/media/nr-cp/2005/2005_32bk2_e.html (accessed February 2008)
- Kalkstein LS (1991) A new approach to evaluate the impact of climate on human mortality. *Environ Health Perspect* 96:145–150. doi:10.2307/3431223
- 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
- Kalkstein LS, Nichols MC, Barthel CD, Greene JS (1996) A new spatial synoptic classification: application to air-mass analysis. *Int J Climatol* 16:983–1004. doi:10.1002/(SICI)1097-0088(199609)16:9<983::AID-JOC61>3.0.CO;2-N
- Kalkstein LS, Barthel CD, Ye H, Smoyer K, Cheng CS, Greene JS, Nichols MC, Kalkstein AJ (1997) The impacts of weather and pollution on human mortality. *Publ In Clim L(1)* p 41
- Keatinge WR, Donaldson GC (2006) Heat acclimatization and sunshine cause false indications of mortality due to ozone. *Environ Res* 100:387–393. doi:10.1016/j.envres.2005.08.012
- Lambert WE, Samet JM, Dockery DW (1998) Community air pollution. In: Rom WN (ed) *Environmental and occupational medicine*. Lippincott-Raven, Philadelphia, pp 1501–1522
- McGregor GR, Watkin HA, Cox M (2004) Relationships between the seasonality of temperature and ischaemic heart disease mortality: implications for climate based health forecasting. *Clim Res* 25:253–263. doi:10.3354/cr025253
- 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
- Nichols MC, Kalkstein LS, Cheng CS (1995) Possible human health impacts of a global warming. *World Resour Rev* 7:77–103
- OMA (2005) *Illness costs of air pollution*. ICAP Summary Report. Ontario Medical Association, Toronto, p 11
- Pirard P, Vandentorren S, Pascal M, Laaidi K, Le Tertre A, Cassadou S, Ledrans M (2005) Summary of the mortality impact assessment of the 2003 heat wave in France. *Euro Surveill* 10:153–156
- Pope CA III, Kalkstein LS (1996) Synoptic weather modeling and estimates of the exposure–response relationship between daily mortality and particulate air pollution. *Environ Health Perspect* 104:414–420. doi:10.2307/3432686
- Qian Z, He Q, Lin HM, Kong L, Bentley CM, Liu W, Zhou D (2008) High temperatures enhanced acute mortality effects of ambient particle pollution in the “oven” City of Wuhan, China. *Environ Health Perspect* 116:1172–1178
- 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
- Rocklöv J, Forsberg B (2008) The effect of temperature on mortality in Stockholm 1998–2003: a study of lag structures and heatwave effects. *Scand J Public Health* 36:516–523. doi:10.1177/1403494807088458
- Ross T, Lott N (2003) *A Climatology of 1980–2003 Extreme Weather and Climate Events*. National Climate Data Center Technical Report No. 2003-01, p 14
- Schwartz J (2000) Assessing confounding, effect modification, and thresholds in the association between ambient particles and daily deaths. *Environ Health Perspect* 108:563–568. doi:10.2307/3454620
- Schwartz J, Spix C, Wichmann HE, Malin E (1991) Air pollution and acute respiratory illness in five German communities. *Environ Res* 56:1–14. doi:10.1016/S0013-9351(05)80104-5
- 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
- Shin HH, Stieb DM, Jessiman B, Goldberg MS, Brion O, Brook J, Ramsay T, Burnett RT (2008) A temporal, multicity model to estimate the effects of short-term exposure to ambient air pollution on health. *Environ Health Perspect* 116:1147–1153
- Stieb DM, Burnett RT, Beveridge RC, Brook JR (1996) Association between ozone and asthma emergency department visits in Saint John, New Brunswick, Canada. *Environ Health Perspect* 104:1354–1360. doi:10.2307/3432974
- Toronto Public Health (2001) *Toronto air quality index health links analysis*. Technical Report. Toronto Public Health, Toronto, p 40
- Toronto Public Health (2004) *Air pollution burden of illness in Toronto: 2004 summary*. Technical Report. Toronto Public Health, Toronto, p 19
- Vedal S, Brauer M, White R, Petkau J (2003) Air pollution and daily mortality in a city with low levels of pollution. *Environ Health Perspect* 111:45–51
- Wong CM, Vichit-Vadakan N, Kan H, Qian Z, the PAPA Project Teams (2008) *Public health and air pollution in Asia (PAPA): a multicity study of short-term effects of air pollution on mortality*. *Environ Health Perspect* 116:1195–1202
- World Health Organization (2004) *Health aspects of air pollution: results from the WHO project “systematic review of health aspects of air pollution in Europe.”* World Health Organization, Report E83080. WHO Regional Office for Europe, Copenhagen, p 24