EXECUTIVE SUMMARY

Many studies have examined how human-made factors such as atmospheric pollutants affect human health; many others have focused on how natural stressors such as extreme temperature events (e.g., heat) influence death rates. However, the differential and combined impacts of weather and air pollution (including pollen) on human health are poorly understood. The scientific/health experts attending the *Canadian Climate Change and Health Vulnerability Assessment 2006* workshop (February 17 & 18, 2004, Ottawa) hosted by Health Canada recognized that one of the priority research areas for assessment is the synergistic and differential impacts of extreme weather and air pollution on human health. These can be measured using the synoptic weather typing approach, which evaluates the proportion of elevated mortality (above the baseline) associated with extreme temperature events (heat/cold) and various air pollutants under current and future climates.

Extreme temperature events (heat/cold) are responsible for a greater number of deaths in the world than most other atmospheric hazards (e.g., floods, hurricanes, blizzards, ice storms). For example, in Western Europe, over 11,000 deaths may have been associated with the record-breaking heat wave event of 2003 (World Health Organization 2003). In the U.S. an estimated 10,000 deaths were related to oppressive heat during the summer of 1980 (Ross and Lott 2003).

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 (WHO 2004). A 2004 report released by Toronto Public Health estimated that about 1,700 premature deaths each year in Toronto are associated with acute exposures to ozone (O_3), nitrogen dioxide (NO_2), carbon monoxide (CO), and sulphur dioxide (SO_2) and chronic exposures to fine particulate matter ($PM_{2.5}$). Of these, about 700 are attributable to acute exposures alone. The Ontario Medical Association (OMA) has estimated that, based on acute exposure to O_3 and PM, air pollution in Ontario results in approximately 1,900 premature deaths per year in Ontario and over $1 billion in direct costs to Ontario's medical system (2000).

Balbus and Wilson (2000) indicated that, although most of the previous published reports addressed the possible impact of climate change on health, only a small minority presented rigorous scientific research involving data collection, statistical analysis, or simulation modeling. Except for heat-related mortality and extreme event impacts, the majority of published reports, including those appearing in major scientific journals, have only speculated about possible health impacts resulting from climate change. We believe the current study could make a significant contribution to the research by projecting the potential health impacts of future climate and air pollution concentrations using rigorous scientific research methods.

In this study, investigators have undertaken a modeling exercise and made use of existing data from reliable sources; levels of uncertainty in the data have been minimized through careful quality assurance and data management according to accepted practices. The models, their rationale and assumptions are carefully outlined and, most importantly, a formal model result verification process has been built into the whole exercise. The results of the verification, based on historical observations of the outcome variables predicted by the models, showed surprisingly good agreement.

Purpose of the study. The Intergovernmental Panel on Climate Change (IPCC 2001a) has projected that the global mean temperature could increase 1.1 – 3.1^{o}C at the time of carbon dioxide (CO_2) doubling. As a result of such warming and extreme hot weather events associated with climate change, the heat-related human health risk is expected to rise significantly in the 21st century. Although the IPCC (2001a) acknowledge that "population health is an important integrating index of the effects of climate change on ecosystems, biophysical processes, physical environmental media, and the social-economic environment," many gaps in our knowledge about this impact remain.

Many studies have examined ways that human-made factors such as atmospheric pollutants affect human health, while others have focused on ways that natural stressors such as extreme weather events influence death rates. Differential impacts of both human-made and natural factors on human health, however, are poorly understood. The purpose of this study, then, is to improve our understanding of differential impacts of extreme temperatures (heat/cold) and air pollution on human mortality under current and future climates in south-central Canada, and to provide the scientific measures that municipal governments will require to develop or enhance the extreme temperatures/air pollution emergency response plan under management legislation.

Overall, this study can be divided into two major parts: (1) development/validation of the models on differential impacts of extreme weather and air pollution on human mortality using historical data, and (2) assessment of climate change impacts on human health using downscaled future global climate model (GCM) scenarios and projected future air pollution concentrations. The overarching purpose of this study is to investigate differential and combined impacts of extreme temperatures (heat/cold) and air pollution on human mortality under current and future climates for four selected cities (Montreal, Ottawa, Toronto, Windsor) in south-central Canada. This study aims to provide decision makers with scientific information needed for public policy risk identification and assessment, as well as for improvement of the adaptive capacity of the health infrastructure in south-central Canada in response to projected human health impacts of climate change. The results from this study are intended to contribute to the *Canadian Climate Change and Health Vulnerability Assessment 2006* and to the development of a national strategy on human health adaptation policies in response to projected global warming. Moreover, the results of the study have the potential to inform the development of a heat/air pollution-health watch/warning system to support municipal government programs that serve to protect populations. Furthermore, the results from this study, expressed as elevated mortality above the baseline associated with various environmental factors (e.g., heat, cold, pollutants) under current and future climates, will help governmental agencies and stakeholders to develop better policies on health protection and to balance policy decisions. The results of this study have greatly enhanced current understanding of environmental problems related to human health in south-central Canada, and allowed the recommendation of adaptation policies that will reduce risks to populations in this region.

Organization of the report. The report is organized as follows: Section 1 provides information on research rationale, objectives, and study area. Section 2 offers a review of previous research related to this report, such as synoptic weather typing, statistical air pollution prediction models, health impacts of weather and air pollution, statistical downscaling, and health impacts of climate change. Section 3 discusses the collection and treatment of data used in the study, including surface and upper-air weather data, air pollution data, human mortality, aeroallergens, and climate change scenarios. Section 4 describes the research design and methodology, while Section 5 discusses the findings of the study. Section 6 outlines a possible adaptation action plan that governmental agencies could use to protect vulnerable populations who have a heightened sensitivity to heat and air pollution. The limitations and uncertainties of the study are discussed in Section 7, and final conclusions and recommendations are offered in Section 8. References are given in Section 9.

Data used in the study. Meteorological data used in the study included six-hourly surface observations from each city's international airport as provided by Environment Canada (1953–2000) as well as upper-air reanalysis data from the U.S. National Centers for Environmental Prediction (NCEP) (1958–2000). The hourly air pollution measurements of O_3, NO_2, CO, SO_2, and coefficient of haze (COH) collected by the National Air Pollution Surveillance (NAPS) network, Environment Canada were used in the study (O_3: 1980–2000, rest of the pollutants: 1974–2000). Although COH is a proxy measure for PM, both $PM_{2.5}$ and PM_{10} were excluded from the study due to a lack of long-term data (i.e., less than three years). Health outcome data used in the study were the record-level mortality data (i.e., data for each death) from Statistics Canada (1954–2000). The future projected weather data consisted of output from three Canadian global climate models (CGCM1 IPCC IS92a and CGCM2 IPCC SRES A2 and B2) for three spans of time (1961–2000, 2040–59, 2070–89) and two U.S. Geophysical Fluid Dynamics Laboratory (GFDL) models (GFDL R30 Coupled Climate Model IPCC SRES A2 and B2) for three spans of time (2010–29, 2040–59, 2070–89). Aeroallergens data included grass, weed, and tree pollen data from Aerobiology Research Laboratories (1993–2000 for Ottawa; 1994–2000 for the other cities).

Key methods used in the study. The following methodologies were used in the study:
1. Synoptic weather typing consisting of principal components analysis (PCA), a clustering procedure, and discriminant function analysis.
2. Regression analysis including multiple stepwise regression, logistic regression, cumulative logit regression, orthogonal regression, and Poisson regression.
3. Statistical downscaling methods comprising PCA or Empirical Orthogonal Functions (EOF), multiple stepwise regression, orthogonal regression, robust stepwise regression, and cumulative logit regression.
4. High-level computer languages and software to develop the codes for achieving study objectives, including Statistical Analysis System (SAS), Fortran, MATLAB, and S-PLUS.

Findings from the study. Findings from this study of the differential and combined impacts of extreme weather and air pollution on human mortality are significant for both historical analysis under the current climate and future assessments under projected climate change scenarios. The major findings of the historical analysis are as follows:

- The annual average elevated mortality associated with extreme temperatures and air pollution, based on 1954–2000 data, was 1,082 (the 95% confidence interval [CI]: 1017–

1147), 1,047 (95% CI: 994–1101), 463 (95% CI: 438–486), and 327 (95% CI: 310–343) in Montreal, Toronto, Ottawa, and Windsor, respectively. Of these, the average number of premature deaths associated with hot weather was 121, 120, 41, and 37, and with air pollution was 818, 822, 368, and 258. The air pollution-related mortality in Toronto predicted by this study (705 premature deaths in 1999) is consistent with the findings of a recent study conducted by Toronto Public Health (695 premature deaths in 1999 based on acute exposures to pollutants) (2004).

- To effectively present the effects of air pollution on elevated mortality over the past 25 years, five-year-averaged annual elevated mortality associated with air pollution for the period 1974–2000 was calculated. Across the study area over the 25-year period, annual mean air pollution-related mortality was lowest during the period 1981–85. On average, across the study area, annual mean air pollution-related mortality for the period 1981–85 was more than 15% lower than that for the period 1974–80, and more than 20% lower than that for the period 1986–90. During the 1974–80 period, higher air pollution-related mortality could be associated with higher SO_2 and CO levels; during the 1986–2000 period, increased air pollution-related mortality could be associated with increases in O_3 concentrations.

- The proportion of elevated mortality associated with extreme temperatures and air pollution was consistent across the study area. Extreme temperatures (heat/cold) were usually associated with roughly 20% of the total elevated mortality, while air pollution was associated with the remaining 80%. Within air pollution-related weather types, three pollutants (O_3, NO_2 and SO_2) were associated with approximately 75% of the total air pollution-related mortality across the study area. The remaining 25% was almost evenly associated with CO and COH, the other two pollutants addressed in the study. Of the five pollutants, O_3 was most significantly associated with elevated mortality in each city, making up one-third of the total air pollution-related mortality.

- Daily mean heat-related mortality was much higher than mortality associated with air pollution and comfortable weather (neither hot nor cold, and where air pollution was low), especially in Montreal and Toronto. In Montreal, daily mean elevated mortality associated with extreme hot weather [5.3 (95% CI: 4.7–6.0) deaths/day] was twice as high as that associated with comfortable weather [2.7 (95% CI: 2.5–2.8) deaths/day]. In Toronto, daily heat-related mortality was 4.6 (95% CI: 4.1–5.1), slightly higher than that found in another recent study (4.2 deaths/day) (Sheridan and Kalkstein 2004).

- Across the study area there was a significant correlation between the actual occurrence of heat-related mortality events and that estimated by the models. The model prediction accuracy rate was very high—85–100%—when using an elevated mortality forecast likelihood of 0.9 (a 90% probability that elevated mortality would occur that day due to heat). Specifically, the predicted number of elevated mortality events, measured in days per year, was 5.0 (Montreal), 2.5 (Toronto), 1.8 (Windsor), and 1.0 (Ottawa). The heat-health prediction models resulting from this study could serve as the basis of a heat-health warning system for each of the cities, using the different likelihood thresholds of elevated mortality occurrence in practice (e.g., 0.9, 0.8, and 0.6).

- The ratio of daily mean elevated mortality associated with extreme temperature-related weather and high air pollution weather types to that related to comfortable weather types can be considered to be a measure of extreme temperature- (heat/cold)/air pollution-related health risk. The results showed that the heat-related health risk for elderly people and for those with circulatory (or cardiovascular) illness was significantly higher than that for all other individuals across the study area, ranging from 1.08 to 1.52. The cold-related health risk for people with respiratory illness was also significantly higher, ranging from 1.12 to 1.21. The air pollution-related health risk for elderly people was significantly higher in all selected cities except Windsor; these risks, however, were much lower than those associated with extreme temperatures. It is noteworthy that the northernmost city—Montreal—had the highest heat-related health risk and the southernmost city—Windsor—had the highest cold-related health risk. It is noteworthy that for all cities except Toronto air pollution-related health risks of nontraumatic total mortality were generally consistent with those from a study of Burnett et al. (1998), although the methodology used in each study differed.

- Mortality from ischemic heart diseases significantly increased when snowfall occurred the day of and the day before the deaths across the study area. For example, the difference in mortality between the days with snowfall amount being one standard deviation above the overall mean (>6.8 cm and in Montreal and >4.3 cm Toronto) and snow-free days is 0.94 for Montreal and 0.84 for Toronto (an increase of 55% and 56% in comparison with daily mean deaths of snow-free days). The corresponding values for Ottawa and Windsor are 0.22 and 0.18 (increased by 34% and 36%), respectively.

- Extreme temperature- (heat/cold) and air pollution-related potential years of life lost (PYLL) due to premature death caused by the given disease were investigated for each of the selected cities. PYLL is defined in this study as the number of years of life lost when a person dies prematurely from any cause before the age of 75. The relationships between PYLL and extreme temperatures (heat/cold) and air pollution are usually not statistically significant. Only cold weather-related PYLL is significantly greater than that associated with comfortable weather types in the two larger cities—Montreal and Toronto, and the hottest weather-related PYLL is significantly greater in Montreal. However, the corresponding PYLL associated with some of air pollution weather groups is lower. This finding implied that air pollution-related health risk, in terms of death for elderly people, was significantly higher across the study area.

- Across the study area there was no evidence of a significant relationship between traffic accidental mortality and freezing rain events, or between respiratory mortality and pollen. This may be due to the small daily mortality counts from these disease categories. To adequately evaluate these relationships, alternative health outcome data, such as hospital admissions, should be used as these will provide a larger sampling size.

In addition to significant findings from the historical analysis, the results from the future assessments on health impacts of extreme temperatures and air pollution were also significant. The major findings from the future assessments are as follows:

- Two independent methods, based on (1) changes in frequency of weather types and (2) future climate and air pollution scenarios, were used to estimate future extreme temperature-related weather and air pollution-related mortality for the five GCM climate change scenarios. The results from both methods were very similar. Averaging the five GCM scenarios, the model predictions were as follows:
  1. Across the study area, heat-related mortality could more than double by the 2050s and triple by the 2080s.
  2. By the 2050s, cold-related mortality could decrease by about 45% for Montreal and Ottawa, and by 60% for Toronto and Windsor; by the 2080s, the percentage decrease could be similar across the study area (60–70%).
  3. With no increase in emissions (Scenario II), air pollution-related mortality could increase across the study area about 20–30% by the 2050s and about 30–45% by the 2080s. This increase would be largely driven by increases in ozone-associated elevated mortality.

- When the population's acclimatization to the increased heat was taken into account, projected heat-related mortality was significantly reduced across the study area. By the 2050s, heat-related mortality would increase by 70–90% and, by the 2080s, by 120–140%, across the study area with slightly higher values projected for Montreal and Ottawa.

- If a logistic regression likelihood of 0.9 was used as a cut-off threshold for a heat-health warning call, the number of days that meet the threshold would dramatically increase by the middle and latter part of this century. Within-the-hottest-weather-type (HA1) elevated mortality occurrence prediction models from logistic regression analysis were used to estimate changes in the number of days under future projected climate. On average, under the five climate change scenarios, by the 2050s the annual number of days would be 3.9–7.4 across the study area; by the 2080s, the corresponding days would be 5.5–10.7.

- Much effort has made to develop the hourly statistical downscaling methodology used in this study. To evaluate the performance of the downscaling models, the data distribution of each observation variable used in the study was compared with that resulting from Canadian CGCM historical runs in the same time period (1961–2000). The results showed that data distributions of the two were very similar for all weather elements, thus suggesting that the downscaling methods developed for this study performed well in downscaling hourly weather variables. The small differences between downscaled historical runs and observations were considered for correction of future elevated mortality assessments and projected air pollution concentrations.

- On average, under the five climate change scenarios, by the 2050s the number of days with 3:00 PM temperatures ≥30°C could more than double (from the current average of six days in Montreal, eight in Ottawa, eight in Toronto, and 15 in Windsor). By the 2080s, the number of days could more than triple in Windsor, nearly quadruple in Toronto and Ottawa, and more than quadruple in Montreal. However, the study found that, taking into account projected frequencies of future weather types and future weather and air pollution scenarios, by the 2080s projected heat-related mortality would not increase in direct correspondence to the number of high-temperature days. This suggests that estimates of future heat-related mortality do not rely only on changes in temperature; variables other than temperature, including other weather variables and air pollution levels, can also affect human health.

- IPCC (2001b) pointed out that "climate change may increase the concentration of ground-level ozone, but the magnitude of the effect is uncertain. For other pollutants, the effects of climate change and/or weather are less well studied." In this study, future air pollution concentrations for five pollutants (O_3, NO_2, CO, SO_2, and COH) were estimated using historical analysis and downscaled climate change scenarios. For all pollutants except O_3, three scenarios were proposed to reflect the possible impacts of future pollutant emission control policies: Scenario I: emissions decrease by 20% by 2050 and 32% by 2080; Scenario II: emissions remain at the same level by 2050 and 2080 as at the end of the 20th century, and Scenario III: emissions increase by 20% by 2050 and 32% by 2080). Across the study area, with a few exceptions, under Scenario I the number of low pollution days (concentration below the overall mean) could increase while the number of high pollution days (concentration one standard deviation above the overall mean) could decrease. Under Scenario III the number of low pollution days could generally decrease and the number of high pollution days generally increase. Similarly, under Scenario II the number of high pollution days could generally increase.

  As O_3 typically results from a photo-chemical reaction between solar radiation and NO_2, future O_3 concentrations were estimated based on both predicted future climate scenarios and projected NO_2 concentrations under the three emission scenarios. Based on the climate change scenarios and air pollution Scenario III, moving northeast to southwest across the study area, the annual total number of poor O_3 days (one-hour maximum $O_3 \geq 81$ ppb) could increase by 4–11 days by the 2050s, and by 10–20 days by the 2080s; good O_3 days (one-hour maximum $O_3 \leq 50$ ppb) could decrease by 24–40 days by the 2050s, and by 42–52 days by the 2080s.

Key recommendation resulting from the study. The key recommendation resulting from this study is that an effective adaptation plan be developed to reduce population health risks resulting from climate change. One of the key components of developing such a plan is implementing early warning systems (Warren and Riedel 2004). These systems could incorporate the findings of this study that, for each of the four cities, significant relationships exist between elevated mortality and weather/air pollution conditions within hot weather types. The results from this study could be used to enhance the effectiveness and utility of such a watch/warning system for south-central Canada, becoming an adaptive approach to addressing both the current climate and ongoing future climate change. Another recommendation is that the results and methods of this study be used to develop municipal snow-related health risk prediction models, not only to institute life-saving intervention plans in a more timely manner, but also to help predict elevated workload within hospitals/emergency rooms and thereby support more effective targeting and delivery of healthcare services. However, to more effectively predict cold/air pollution-related human health risks, more research should be conducted using a larger daily sample size of health outcomes, such as hospital admissions.

Major assumptions and uncertainties of the study. Although there is a significant correlation between the occurrence of heat-related mortality events and the modelled results across the study area, the major limitation of the study was that the daily mortality counts were too small to use in developing daily-based prediction models for air pollution and cold weather-related mortality. More studies using alternative health outcome data (e.g., hospital admissions) rather than mortality are needed to determine significant relationships for the following aspects:

- Development of daily based prediction models of health impacts of air pollution and cold weather conditions
- For small cities, development of heat-related health risk prediction models
- Determination of impacts of aeroallergens on human health (e.g., respiratory diseases)
- Determination of effects of freezing rain on traffic accidents.

Governmental agencies and stakeholders would benefit from the use of both mortality and morbidity data in the creation of heat-/cold-/air pollution-related health risk prediction models; these models would support programs not only to prevent death but also to minimize illness due to extreme temperatures and air pollution. The Toronto Heat-Health Alert System (HHAS) and cold-/air quality-health alert programs would be improved if they were developed based on both mortality and morbidity analyses.