8.1 Major Findings of Historical Analysis

8.1.1 *Synoptic Weather Typing*

The automated synoptic weather typing was comprised of principal components analysis, an average linkage clustering procedure, and discriminant function analysis. Using six-hourly surface observations of temperature, dewpoint, sea-level air pressure, total cloud cover, and west–east and south–north winds, the weather typing procedures identified 35–40 major weather types across the study area.

To validate the identified weather types, discriminant function analysis was used to assign each day of the validation dataset (1977, 1983–86, 1992, 1994, 1996, and 1998) into one of the weather types predetermined from the developmental dataset. The results were found to be similar for both developmental and validation datasets, suggesting that the discriminant function analysis performed well in verifying or predicting the weather types.

8.1.2 *Weather Types Link with Air Pollution*

Hot and cold weather types were determined before identifying the weather types most associated with high air pollution levels. For each of the four selected cities, three hot weather types were identified; the rest of the weather types usually had lower mean afternoon temperatures. The criterion for determining the cold weather type depended on the difference of January mean afternoon temperature among the cities. Identified cold weather types were combined as a cold weather group.

Since each of the weather types represented a distinctive air mass and synoptic signature, a specific regime of air pollution was related to each type. Two measurements—within-weather-type mean air pollution concentrations and frequency of high air pollution episodes—were used to identify weather types associated with high air pollution concentrations. Results indicated that mean pollution concentrations varied considerably among the synoptic weather types. For example, some weather types have a mean O_3 concentration that is much greater than the overall mean; others are associated with concentrations much lower than the overall mean.

Similar methods were also applied to the remainder of the pollutants for each of the selected cities. Some weather types were significantly associated with high air pollution concentrations for numerous pollutants (up to five); other types possessed good air quality and were not significantly related to any pollutant. Weather types were divided into ten groups: three hot weather-related (including air pollution) groups (HA1, HA2, HA3), one cold weather-related (including air pollution) group (CA), five air pollutant-related groups (O_3, CO, COH, SO_2, NO_2), and one "other" group (relatively good air quality and comfortable weather conditions). In the study area, all three hot weather types were associated with high O_3 concentrations; however, there were some individual cold weather types not significantly associated with high air pollution levels. In this study, such cold weather types were combined with other cold-/air pollution-related weather types because of the small size of the weather types.

8.1.3 *Impacts of Weather Characteristics on Air Pollution Concentrations*

It is apparent that meteorological characteristics of the weather groups are consistent across the study area, especially for air temperature and dewpoint. In each of the selected cities, besides the three hot weather groups, the O_3-related weather type is the warmest of the weather groups. The wind directions within some air pollution-related weather types were generally consistent between the cities across the study area; for example, SO_2-related weather types in all four cities were frequently associated winds from the west. In Montreal and Ottawa, O_3-related weather types were frequently associated with southwesterly winds; in Toronto they were associated with south-southeasterly winds, and in Windsor with south and northeasterly winds. The relationships between air pollution concentrations and wind direction within air pollution-related weather types imply that, in addition to the presence of local pollutant sources, air pollutants in south-central Canada are often transported from the U.S. and adjacent Canadian provinces by airflow.

It is interesting to note that O_3-related weather types in Toronto are mostly associated with south-southeasterly winds, which implies that high O_3 concentrations in Metropolitan Toronto could be transported across Lake Onatrio from other Canadian or U.S. cities. The evidence for this is that observed O_3 concentration at Toronto Island is significantly higher than that in Metropolitan Toronto. Mean one-hour maximum O_3 concentrations for the period May–August 2003 were 65.5 ppb at Toronto Island and 53.5 ppb in Metropolitan Toronto. A one-tailed *t*-test confirmed that these two means were statistically significantly different (significant level $\alpha<0.0001$).

8.1.4 *Mortality Baseline*

Following determination of the ten weather groups, the weather group "other" (good air quality (i.e., low pollution concentration) and comfortable weather conditions), represents non-weather- and non-air pollution-related weather types. By using these "other" weather types, mortality baselines were constructed by calculating the within-other-weather-group mean mortality from anomaly data against the inter-annual trends (Figure 20). A positive mortality residual (above the baseline) should represent the elevated mortality associated with extreme temperatures (heat/cold) and air pollution. In other words, the baseline could represent normal or natural deaths without the effects of extreme temperatures and air pollution.

This mortality baseline used here differs from that of previous studies. For example, a recent study (Sheridan and Kalkstein 2004) used the three-year running mean of daily mortality (centered on the year in which the particular day lies) to represent the mortality baseline for development of Heat Watch–Warning System currently piloted in many cities over the world, including Toronto. This baseline was developed using all days, including hot and polluted days; consequently, some heat-/air pollution-related mortality was removed, which should be included in the analysis. In addition, using the three-year running mean would also remove some inter-annual heat impacts on mortality.

8.1.5 *Elevated Mortality Associated with Extreme Temperatures and Air Pollution*

The annual average elevated mortality associated with extreme temperatures and air pollution, based on 1954–2000 data, was 1,082 (95% 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 number of premature deaths associated with hot weather were 121, 120, 41, and 37 respectively, while the number associated with air pollution were 818, 822, 368, and 258. 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).

The proportion of elevated mortality associated with extreme temperatures and air pollution was consistent across the study area. Extreme temperatures (heat and cold) were typically associated with more than 20% of total elevated mortality across the study area; air pollution was related to the remaining 80%. Within air pollution-related weather types, three pollutants—O_3, SO_2, NO_2— were associated with about 75% of the total air pollution-related mortality across the study area. The remaining 25% was almost evenly associated with COH 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.

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

Daily mean heat-related mortality was much higher than that associated with air pollution-related and comfortable weather types (neither hot nor cold, and where air pollution was low), especially in Montreal and Toronto. Daily mean elevated mortality within the extreme hot weather type in Montreal was twice as high as that associated with the comfortable weather types [5.3 (95% CI: 4.7–6.0) deaths per day versus 2.7 (95% CI: 2.5–2.8)]. In Toronto, the daily heat-related mortality in Toronto 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).

The ratio of the daily mean elevated mortality associated with extreme temperature-related weather and high air pollution weather types to that associated with the comfortable weather type can be considered 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 those with circulatory or cardiovascular illness was significantly higher 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; however, the ratios were much lower than those associated with extreme temperatures. It is noteworthy that the northernmost city (Montreal) had the highest heat-related health risk of the four cities, 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 by Burnett et al. (1998), although the methodology used in each study differed.

8.1.6 *Within-weather-type Potential Years of Life Lost*

The extreme temperature- (heat/cold) and air pollution-related 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 typically 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 the 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.

8.1.7 *Air Pollution "Day-to-day" Prediction*

A robust stepwise regression analysis was performed on all days of the developmental dataset for each of weather groups (hot/AP, cold/AP, AP, and other) to develop air pollution prediction models for each air pollutant and each city. The dependent variable is the daily mean and one-hour maximum concentrations of O_3, CO, COH, SO_2, and NO_2. The independent weather variables used in the regression procedure are derived from six-hourly and daily surface observations and six-hourly upper-air reanalysis data. Those predictors were selected based on analyses of relationships between individual pollutants and predictors as well as results of various previous studies. For each city, 40 air pollution prediction models were developed for five air pollutants of daily mean and one-hour maximum concentrations and four weather groups.

Generally, air pollution prediction models for daily mean air pollution concentrations are more robust than those for one-hour maximum concentrations in the four cities. Across the study area, close to 75% of the 80 mean air pollution prediction models possessed a model $R^2 > 0.5$; close to 50% possessed a model $R^2 > 0.6$. Although the relationships between one-hour maximum values from observations and model predictions are usually weaker than daily mean prediction models, most of the O_3 one-hour maximum prediction models still possessed a model $R^2 > 0.6$.

Air pollution prediction algorithms were applied to the nine-year validation dataset in evaluating the performance of air pollution prediction models. The results show that, across the cities, patterns of the R^2s among the pollutants are similar between model development and validation (except for slightly smaller R^2 values from the model validation datasets).

8.1.8 *Regression Analysis on Elevated Mortality*

A stepwise logistic regression was used in the study to develop heat/air pollution-health prediction models because the results from logistic regression were better than those from other regression methods tested in the study. In addition, the output from the logistic regression procedure is easy to interpret in practice, as it is in the form of probability of elevated mortality occurrence. The stepwise logistic regression was employed for all days within each of three hot weather types. The logistic regression model identified elevated mortality predictors across the study area that included temperature, humidex, day in sequence of the hot weather type, time of season, sea-level air pressure, total cloud cover, and concentrations of the different pollutants.

There was a significant correlation between the occurrence of heat-related mortality events and the modelled results across the study area. The model detection accuracy rate was very high, ranging from 85% to 100%, when using an elevated mortality forecast likelihood of 0.9, representing a 90% probability that elevated mortality would occur that day due to heat. The number of elevated mortality events identified by the models was 5.0, 2.5, 1.8, and 1.0 days per year for Montreal, Toronto, Windsor, and Ottawa, respectively, when a prediction likelihood of 0.9 was used as a cut-off. The heat/air pollution-health prediction models resulting from this study can be used to develop a heat-health warning system for each of the cities in terms of the different warning levels, using the various likelihood thresholds of elevated mortality occurrence in practice (e.g., 0.9, 0.8, and 0.6). The model detection accuracy rate and FAR depend on the use of cut-off probability thresholds. As a result, the authors recommend that various cut-off probability thresholds be used in the cities studied to balance the number of health system calls across the study area.

The daily mortality regression results showed that there was a strong relationship between elevated mortality and the model predictions in the hot weather types, but it was necessary to use a different regression procedure for the rest of the weather types in order to obtain suitable regression models. Within each of the eight weather groups (hot, cold, comfortable, and five air pollutant-related weather types), the data were regrouped using a ranking procedure. The advantage of the ranking procedure is that it enhances relationships between elevated mortality and the ranking factor within a certain weather or air pollution type as well as eliminates the impacts of other factors.

Many weather variables (such as surface and upper-air temperatures, humidex, wind chill) and all selected pollutants (O_3, CO, COH, NO_2, SO_2) were statistically significantly associated with elevated mortality in the different weather types. The relationships between elevated mortality and weather and air pollution predictors are outlined as follows:

1. Thermal and moisture weather variables, but not air pollutants, were significantly associated with elevated mortality in the hot weather types for Montreal; however, in the other cities, both temperature and O_3 were found statistically significantly to contribute to elevated mortality.
2. In cold weather types, low temperatures, low windchill equivalent temperatures, and high air pollution concentrations contributed to elevated mortality across the study area.
3. In five pollutant-related weather types, both weather and air pollution conditions were significantly important to elevated mortality in all the selected cities.

4. In comfortable weather types, air pollution levels, but not weather variables, were significantly associated with elevated mortality across the study area.

8.1.9 *Snowfall Impacts on Ischemic Heart Diseases*

Across the study area, mortality from ischemic heart diseases significantly increased when snowfall occurred on the same and previous days as the deaths. For example, in Montreal and Toronto, the differences in mortality between the days with snowfall amounts one standard deviation above the overall mean(>6.8 cm in Montreal and 4.3 cm in Toronto) and snow-free days were 0.94 and 0.84 respectively (an increase of 55% and 56% in comparison with daily mean deaths of snow-free days). The corresponding values for Ottawa and Windsor were 0.22 and 0.18 (increases of 34% and 36%), respectively.

8.1.10 *Freezing Rain Impacts on Traffic Accident Mortality and Pollen Impacts on Respiratory Mortality*

Across the study area there was no evidence of significant relationships between traffic accident mortality and freezing rain events nor between pollen and respiratory mortality. One reason might be the small daily mortality counts from these disease categories. In order to evaluate such relationships, alternative health outcome data, such as hospital admissions, should be used since this would provide a larger sampling size.

8.2 Major Findings on Future Climate Change Impact Assessments

In addition to these significant findings from the historical analysis, the results from the future assessments on health impacts of extreme temperatures and air pollution were also significant.

8.2.1 *Daily and Hourly GCM Statistical Downscaling*

Much effort was made to develop the hourly statistical downscaling methodology used in this study. To evaluate performance of the downscaling models, the data distribution of each variable used in the study from observations was compared with that from the Canadian CGCM historical runs over the same time period of 1961–2000. The results showed that data distributions for downscaled historical runs and observations were very similar for all weather elements. This result implied 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 in future elevated mortality assessments and projected air pollution concentrations.

Averaging the five GCM scenarios, the study predicted that the number of days with 3:00PM temperature ≥30°C could more than double by the 2050s across the study area (from the current average of 6–15 days from Montreal to Windsor). By the 2080s, the corresponding days could more than triple in Windsor, nearly quadruple in Toronto and Ottawa, and more than quadruple in Montreal. However, the results of this study, using changes in frequencies of future weather types and characteristics of weather and air pollution variables, suggest that by the 2080s future projected heat-related mortality would not increase to the same degree. This implied that the estimates of future heat-related mortality do not depend only on changes in temperature, since not only temperature, but also other weather variables and air pollution levels, can affect human health.

8.2.2 *Assessment of Future Air Pollution Levels*

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, SO_2, NO_2, CO, and COH) were estimated using historical analysis, downscaled climate change scenarios, and assumed future pollutant emission control policies. In estimating future pollution, three scenarios were considered for all pollutants except O_3: Scenario I: emissions decreasing by 20% by 2050 and 32% by 2080; Scenario II; emissions remaining at the same level by 2050 and 2080 as at the end of the 20th century; Scenario III: emissions increasing by 20% by 2050 and 32% by 2080. As O_3 is typically produced by photo-chemical reactions between solar radiation and NO_2, future O_3 concentrations were estimated based on both future climate scenarios and projected NO_2 concentrations under these three emission scenarios.

Based on the climate change scenarios and air pollution emission 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) would 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) would decrease by 24–40 days by the 2050s, and by 42–52 days by the 2080s. For the remaining pollutants, with a few exceptions under emission Scenario I, the number of low (concentration below the overall mean) pollution days could increase and high (concentration one standard deviation above the overall mean) pollution days could decrease across the study area. Under air pollution emission Scenario II, the number of high pollution days could increase with a few exceptions. Under air pollution emission Scenario III, the number of low pollution days for all pollutants could generally decrease, while high pollution days could generally increase in response to climate change.

8.2.3 *Future Number of Days with Heat-related Health Risk under the Future Projected Climate*

If a logistic regression likelihood of 0.9 was used as a cut-off threshold for a heat-health warning call, the number of the 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 the 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 number of days would be 5.5–10.7.

8.2.4 *Future Heat/Cold-related Elevated Mortality*

Two independent methods (based on (1) changes in frequency of weather types alone; and (2) future climate and air pollution scenarios) were used to estimate future extreme temperature- and air pollution-related mortality for the five climate change scenarios. The results from both methods were very similar. Averaging the five GCM scenarios, the model predictions are outlined below.

This study estimated that currently there are 121, 41, 120, and 37 premature deaths associated with three hot weather types for Montreal, Ottawa, Toronto, and Windsor, respectively. Across the study area, the models predicted heat-related mortality could more than double by the 2050s and triple by the 2080s.

Estimates also showed that 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, the corresponding decrease would be similar across the study area (60–70%).

8.2.5 *Assessment of Population's Acclimatization to Increased Heat*

When attempting to assess the impacts of global warming on future mortality, population acclimatization to the increased heat needs to be considered. There is evidence that populations tend to acclimatize to increased heat, although the extent to which this happens is unclear. This study estimated acclimatization and, for the sake of comparison, both nonacclimatized and acclimatized estimates have been developed. When population acclimatization to 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 across the study area by about 70–90%, and by the 2080s it would increase about 120–140%; the higher values are projected for Montreal and Ottawa.

8.2.6 *Assessment of Future Air Pollution-related Elevated Mortality*

With no increase in emissions (Scenario II), air pollution-related mortality across the study area could increase about 20–30% by the 2050s and about 30–45% by the 2080s. This increase in the study area is largely driven by increases in O_3-associated elevated mortality.