5.2 AN ANALYSIS OF POSSIBLE CLIMATE CHANGE IMPACTS ON HUMAN MORTALITY IN SOUTH CENTRAL CANADA

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1. INTRODUCTION

Many research studies are available for Canada relating air pollution and human health. For example, Burnett et al. (1994a, 1994b, 1995, 1997a, 1997b, 1999) utilized data on hospital admissions for cardio-respiratory diseases and air pollution data from 1980 to 1994 to conclude that there were positively significant associations between air pollution (e.g., O_3, sulfates) and respiratory diseases in many cities of Canada. Pengelly et al. (2000) investigated the association between the 6 air pollutants (PM_{10}, SO_4, CO, NO_2, SO_2, O_3) and mortality/hospitalizations in Toronto and concluded that three of the six pollutants (NO_2, CO, SO_2) were associated with almost 80% of air pollution-related premature deaths. Stieb et al. (1996) examined the relationships between ozone level and asthma emergency department visits in Saint John, New Brunswick and found that the frequency of the visits was about 33% higher when the daily 1-hour maximum ozone concentration exceeded 75 ppb. Smoyer et al. (1999) investigated heat-related mortality for five large cities in the Toronto-Windsor Corridor and determined that only in Metropolitan Toronto were mean daily heat stress mortality rates (heat index >32°C) significantly greater than non-heat stress mortality (heat index ≤32°C). All of the previous studies examined the health impacts of air pollution or individual weather elements on excess mortalities.

Many of the studies to date have used Poisson regression analysis to evaluate the impacts of air pollution on human health in many regions of the globe. Several researchers have built Poisson regression models for respiratory diseases based on a variety of pollutants as well as daily mean temperature and relative humidity (Schwartz et al., 1991; Hefflin et al., 1994; Dab et al., 1996; Schouten et al., 1996; Vigotti et al., 1996; Peters et al., 2000). Some studies have utilized the same method to analyze the relationships between air pollution and hospital visits for asthma (Schwartz et al. 1993, Pönkä and Virtanen 1996), while others have simply used linear multiple regression to examine the relationship between air pollution and hospital admissions (Samet et al. 1981, Pope 1991, Keiding et al. 1995, Xu et al. 1995, Gordian 1996, Leon et al. 1996). These earlier studies concluded that there existed a significant positive relationship between pollution and human health but a weaker relationship between weather and human health.

Many earlier studies have suffered from several simplifications. For example, in much of the research, daily mean temperature and relative humidity have been used to describe the influence of weather or climate on human health. These weather variables have not sufficiently removed the confounding impacts of weather in a pollution-health analysis (Pope and Kalkstein 1996). Some studies (Kalkstein 1991, Kalkstein et al. 1997) have indicated that offensive weather events can significantly impact acute mortality through a variety of influences since populations may respond to several properties of an entire air mass rather than to individual weather elements such as daily mean temperature. Other studies have tended to use relative humidity to represent atmospheric moisture, which is a highly collinear variable but provides less information than dew point temperature. The dew point temperature is highly conservative on a diurnal level and moderately conservative among various micro-environments (Kalkstein and Corrigan 1986). In addition, previous studies have not been able to deal with the confounding impact of several pollutants and weather variables on human health (Gamble and Lewis 1996) and have tended to consider all days in their analysis, including days with comfortable weather and good air quality conditions. Our study only considered days within the weather types that were most highly associated with elevated mortality and/or high air pollution events, potentially providing more significant relations between weather and human health (Cheng 1991, Kalkstein 1991, Nichols et al. 1995).

Some earlier research on weather-health relations focused on a few individual meteorological elements or weather patterns using subjectively manual grouping methods (Jones et al. 1982, Shope 1991, CDC 1995, Alexander 1998, Benson et al. 2000, Huynen et al. 2001). These classification procedures must be performed manually using day-to-day surface weather maps, which can be exceedingly time-consuming and data-intensive when analyzing a climatological period of many years. In

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some cases, these totally subjective procedures may bias results (Cheng and Kalkstein 1997).

An alternative or supplement to subjective classification procedures is the use of automated synoptic classification, which has been successfully used in climatic impact assessments on human mortality (Kalkstein 1991, Cheng 1991, Nichols, et al. 1995, Pope and Kalkstein 1996, Kalkstein and Greene 1997). This method has been adapted to develop heat-health watch/warning systems that have been successfully implemented in Philadelphia, Cincinnati, Rome, Shanghai and Toronto for the UN Showcase Project. In these studies, an automated synoptic categorization was used, which permits an evaluation of relations among a variety of weather elements rather than the individual elements; the combined impact of several elements is more significant than the sum of their individual impacts (Kalkstein 1991, Pope and Kalkstein 1996, Kalkstein et al. 1997). However, these studies did not examine the synergistic impacts of weather and air pollution on human mortality but only concentrated on heat waves. In addition, in these studies, an average linkage clustering procedure (hierarchical method) and discriminant function analysis (nonhierarchical method) were applied separately. It is expected that the combination of hierarchical and nonhierarchical classification methods produces better classification results with smaller within-cluster variances and larger between-cluster variances (Huth et al. 1993, DeGaetano 1996). In order to get more reasonable classification results, the synoptic classification procedure used in this study will combine the principle components analysis, an average linkage clustering procedure and discriminant function analysis.

2. DATA SOURCES AND TREATMENT

Hourly surface meteorological data for two locations in South Central Canada – Toronto and Montreal International Airports were retrieved from Environment Canada's Digital Archive of Canadian Climatological Data for the summer months (Apr.-Sep.) of 1953-2001. The meteorological data included 3:00AM, 9:00AM, 3:00PM and 9:00PM LST weather station observations of air temperature (^{o}C), dew point temperature (^{o}C), sea-level air pressure (hPa), total cloud cover (tenths of sky cover), wind speed (m s^{-1}) and direction (degrees). A sine-cosine transformation was used to convert wind speed and direction into southerly and westerly scalar velocities. The missing data was interpolated using a temporal linear method when the data was missing for 3 consecutive hours or less; otherwise, days with data missing for 4 or more consecutive hours were excluded from the analysis. Of the total dataset, only 6 and 10 days were interpolated for Montreal and Toronto, respectively; after interpolation, only 4 and 8 days with missing data were deleted from the analysis.

The 6-hourly upper-air reanalysis weather data were retrieved from the U.S. National Centers for Environmental Prediction (NCEP) website. The reanalysis data were available daily for 0600, 1200, 1800, and 0000 UTC for the period 1958-2001 and included a variety of meteorological variables on a 2.5^{o} x 2.5^{o} latitude-longitude grid at 17 standard upper-air pressure levels, including air temperature (^{o}C), relative humidity (%), geopotential height (m), vertical velocity (Ω, Pa s^{-1}), west-east and south-north wind velocities (m s^{-1}). Data from only 6 pressure levels: 1000, 925, 850, 700, 600 and 500 hPa were used in this study since the atmospheric parameters needed to determine both production and type of precipitation are primarily confined to levels below 500 hPa. Although the reanalysis data was available for the entire 50 year period 1948-2001, only the data for the period 1958-2001 was used in this study. Prior to 1958, there were fewer upper-air observations and they were made 3 h later than the current main synoptic time (e.g., 0300, 0900, 1500, and 2100 UTC); as a result, the reanalysis data is considered less reliable (Kistler et al. 2001).

Daily climate change scenarios from the Canadian GCMs (CGCM1 and CGCM2 GHG+A) and the U.S. GCM (GFDL R30 Coupled Climate Model) for 2-time windows in the 21st century (2040-2059 and 2070-89) were used in the analysis. These 2 time windows were selected to coincide with GFDL web-based outputs. In addition, the historical runs of the CGCM1 and CGCM2 from 1961-2000 were used for correction of the model bias; however, historical runs were not available for the GFDL model. As the GFDL outputs are on the sigma level, the variables needed to be interpolated to the upper-air pressure levels. The daily GCM outputs of the surface and upper-air weather variables were downscaled for the selected weather stations in South-Central Canada to derive the future corresponding hourly data.

The daily record-level mortality data for Montreal Island and Metropolitan Toronto from 1950 to 2000 were provided by Statistics Canada. Daily total mortality from all causes was classified on the basis of the International Classification of Diseases (ICD) coding of diagnosis (ICD-6 & 7: 001-795; ICD-8: 000-796; ICD-9: 001-799; ICD-10: A00-R99),

Inter-annual fluctuations existed in the mortality data, showing dramatic upward trends against time in years. These fluctuations resulted from several factors, including changes in total population and population age structure as well as improvements to health care (Kalkstein et al. 1997). However, it is impossible to determine the degree to which each is responsible. Since these non-climatological factors represent confounding influences within the mortality data, the influence of these fluctuations needed to be removed from the dataset. This can be achieved by fitting a polynomial regression line through daily mean mortality rates against time in years. These polynomial regression models were very significant and can explain about 83% to 99% of the data variances for both cities. The predicted mean daily mortality rates for each year (as derived from the regression models) were deemed a baseline value.

The difference between each day's actual number of mortalities and this baseline was calculated and utilized for further analysis. Similarly, the seasonal fluctuations were also removed from the data.

Atmospheric pollution data collected by the National Air Pollution Surveillance (NAPS) network is available from Environment Canada for several locations in both selected cities. The data consist of hourly measurements of ozone (O_3), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), and coefficient of haze (COH). All available data records of air pollutants from 1974 to 2000 (except for O_3) were used in the analysis. O_3 observations were only included in the study for the period 1980-2000 due to different measurement procedures before and after 1980, as recommended by the Ontario Ministry of the Environment (MOE). Based on the length and completeness of the available data records, three and seven monitoring sites were chosen to calculate mean concentrations representing average air pollution conditions for Toronto and Montreal, respectively.

To obtain areal average daily mean and maximum concentrations of atmospheric pollution conditions, the hourly concentrations for each of the 24 hours were calculated based on available observations from the selected sites. An areal average hourly concentration was calculated as long as at least one observation was available in the selected city at that time. Areal average daily mean and maximum concentrations were derived from areal average hourly values. Based on the MOE and NAPS' guidelines, daily mean concentrations were not computed unless 75% of the areal average hourly concentrations were available within a day. Determination of daily maximum concentrations from the areal average hourly concentrations produced different values from the NAPS calculations. According to the NAPS' database, guidelines, given that only 2 observations existed during any time of the day, the bigger concentration would be set as the daily maximum and the lower was set as the daily minimum. In this study, a certain period of the day was identified for determination of daily maximum concentrations. This period, when hourly mean concentrations of atmospheric pollution measurements are greater than the overall average, represented the hours when the highest concentrations could be expected. The daily maximum concentration was determined from all valid observations during an entire day only when at least one observation was available during the period; otherwise, the daily maximum value was missing for the day. After air pollution data treatment, daily mean and maximum air pollution concentrations used in the study only were characterized by only 0.03–1.14% missing data for the selected air pollutants at both cities.

3. METHODOLOGY

3.1 *Automatic Synoptic Categorization*

An automated synoptic classification procedure, based primarily on air mass similarity and differentiation within and between weather types, was used to assign each day of the dataset into a distinctive weather type. The entire suite of 24 weather variables was used in the classification, including: 6 hourly (03:00AM, 09:00AM, 03:00PM, 09:00PM LST) surface weather observations of air temperature, dew point temperature, sea-level air pressure, total cloud cover, south-north and west-east scalar wind velocities.

Classification procedures used in this study were determined using a 2-step process: 1) temporal synoptic weather types were categorized using principal components analysis (PCA) and a hierarchical agglomerative cluster method – an average linkage clustering procedure and 2) using the centroids of the hierarchical weather types as seeds, all days in the dataset were regrouped by a nonhierarchical method – discriminant function analysis. Since the number of weather types was not predetermined, a hierarchical agglomerative clustering procedure is suitable for the initial classification (Kalkstein et al. 1996; Cheng and Kalkstein 1997; Cheng and Lam 2000). The PCA was performed to reduce the 24 intercorrelated weather variables into a small number of linearly independent component variables, which can explain much of the variance within the original dataset. Component loadings were calculated to express the correlation between the original weather variables and the newly formed components. The principal components, which can explain 2% of the total variance or more, were retained to calculate component scores. Days with similar meteorological situations will tend to exhibit approximately similar component scores. The average linkage clustering procedure generated statistical diagnostics to produce an appropriate number of clusters (for details, refer to Boyce, 1996; Cheng and Lam, 2000), and then classified those days with similar component scores into one of the meteorologically homogeneous groups. Following the hierarchical classification, a nonhierarchical classification procedure was used to reclassify all days within the dataset using the centroids of the hierarchical weather types as seeds. In addition to a calendar of daily weather types created by the nonhierarchical reclassification procedure, within-cluster mean values and standard deviations were calculated for the various meteorological variables.

3.2 Identification *of the Weather Types Associated with Elevated Mortality and High Air Pollution Events*

Daily mortality data was used in the identification of the synoptic types which were most highly associated with high numbers of elevated mortality in Toronto and Montreal. The daily mean mortality rate for each type was then determined to ascertain whether the mortality value within the particular weather types was distinctively high or low. In addition, a ratio of the category's occurrence of elevated mortality events (actual frequency) to the occurrence of the category in the entire record (expected frequency) was utilized to determine whether any of the categories were over-represented for elevated mortality events. Categories with ratios significantly greater than 1.0 clearly had a greater proportion of days with elevated mortality events than would be expected based on the frequency of weather types. The statistical χ^2-test was employed to determine whether or not the theoretical frequency among the elevated mortality events was significantly higher than the expected frequency. This method could then be applied to different elevated mortality rates, such as daily mortality with 1, 2, and 3 standard deviations above the overall mean. To identify weather type association with high air pollution concentrations, the similar methods were used.

3.3 *Statistical Downscaling Methods*

The statistical downscaling methods used in the study consisted of 4 steps: 1) The PCA was applied to the domain for all days from 1958 to 2000 for each of reanalysis weather elements, which can identify a reduced set of uncorrelated variables that can account for most spatial relationships in the original dataset (Schubert and Henderson-Sellers, 1997). The spatial relationships can offset from the large scale GCM output that is not capable of reproducing meaningful regional surface climates (Bárdossy, 1994; Bass and Brook, 1997). 2) Regression-based downscaling methods rely on empirical relationships between local scale predictands and regional scale predictors. The multiple regression procedure was employed to analyze the relationships between the surface observations/upper-air reanalysis elements at a single-site of the selected stations and the PCA component variables derived from the NCEP reanalysis data field. 3) To be comparable to the z-score used for the PCA analysis above and remove the GCM model system errors, daily GCM scenarios were standardized by the means and standard deviation of the GCM historical runs, resulting new z-scores. The component scores for each day of the GCM scenarios were determined by multiplying the post-eigenvector matrix (reanalysis data for the period 1958-2000) by the new z-score matrix. The GCM scenario component scores were applied to regression algorithms to produce downscaling GCM scenarios for each of the elements at each of the selected stations. 4) The future hourly values of these elements were estimated based on the historical relationships between the hourly observation and its daily mean as well as other weather predictors, where appropriate.

3.4 *Estimation of Future Elevated Mortality Rates*

The future mean elevated mortality rates were estimated based on within-weather-type historical mean elevated mortality rates and the changes in frequency of future synoptic types. The within-type future mean elevated mortality rates are assumed to be directly proportional to the corresponding historical mean mortality and change in frequency of weather types. The annual mean total number of future elevated mortality rates (*Mort_future*) was estimated using expression

$$Mort_{-future} = \sum_{i=1}^{n} \left(\frac{Freq_i^f}{Freq_i^h} \times Mort_i^h \right),$$

where n is the number of all weather types, $Freq_i^h$ and $Freq_i^f$ are the percentage frequencies of weather type i for historical and future periods, and $Mort_i^h$ is the historical mean elevated mortality rate within weather type i. To estimate future elevated mortality rates caused by different factors (e.g., extreme weather, air pollution), this calculation was applied to heat/cold- and air pollution-related weather types, separately.

4. RESULTS AND DISCUSSION

4.1 *Hierarchical Clustering*

The average linkage clustering procedure was employed to derive clusters possessing similar large-scale synoptic characteristics in terms of the daily 8-component scores for Toronto or Montreal. The numbers of clusters for retention was determined using a variety of statistical tests, including the semipartial R^2, pseudo-F, pseudo-t^2, and explained variance R^2. The semipartial R^2 is the ratio of the increased within-cluster variance after joining two clusters to the variance for the entire dataset. The pseudo-F is the ratio of between-cluster to within-cluster variances. The pseudo-t^2 is the ratio of the increased within-cluster variance after joining two clusters to the variance within each of two clusters (SAS Institute Inc. 1999; Eder et al. 1994). The number of clusters for retention in the model was determined by observing the largest decrease in R^2, the largest increase in both the semipartial R^2 and pseudo-t^2 after joining two clusters and a local maximum in the pseudo-F.

Using the above procedures, **32 major synoptic** weather types with sizes above 100 days or 1% of the total days were identified for Toronto and Montreal, respectively. They are based primarily on differences in their meteorological characteristics for all days from 1953-2001.

4.2 *Nonhierarchical Cluster Modification*

A nonhierarchical method – discriminant function analysis was used to reclassify all days within the dataset using the centroids of the hierarchical weather types as seeds. Approximately 35% of the total days were reclassified. Generally, differences between cluster sizes resulting from the nonhierarchical reclassification were smaller than the originals classified by the hierarchical clustering procedure alone.

To quantify any improvement in cluster structure resulting from the nonhierarchical reclassification, a variety of statistical tests on both classification results were analyzed, such as within- and between-cluster standard deviations and the number of days with extreme weather conditions or temperature above certain critical thresholds. Results from the tests have shown that the cluster structure resulting from nonhierarchical reclassification was better than that using the hierarchical procedure alone. For example, overall between-cluster standard deviations for all weather elements resulting from the nonhierarchical reclassification (discriminant function analysis) were greater, while the corresponding within-cluster standard deviations were smaller. These results were consistent with some previous studies (e.g., DeGaetano 1996). In addition, the nonhierarchical reclassification can capture an additional 5.4% of the total days with 3:00PM LST temperature greater than 30^{o}C in the hot weather types.

4.3 *Weather Types Link with Mortality and Air Pollution*

Since each of the weather types represented a distinctive air mass and synoptic signature, a specific regime of mortality and air pollution should be related to each type. Results indicated that the number of elevated mortality events varied considerably among the weather types. Some weather types have a greater proportion of days with elevated mortality than others.

To identify the synoptic types most highly associated with elevated mortality cases, a category frequency ratio was calculated. This ratio compared the percentage frequency of days with elevated mortality (actual frequency) to the percentage frequency of the weather type within the entire record (expected frequency). A χ^2-test was employed to ascertain that the observed frequencies of elevated mortality cases were significantly different from their expected occurrences (χ^2-test significance level of 0.001).

Following identification of the weather types most highly associated with elevated mortality cases, a similar analysis needed to be completed for air pollution concentrations. The daily maximum and mean air pollution concentrations were used to identify the weather types associated with high pollution concentrations. The methods for identifying the weather types with elevated mortality were applied to determine the air pollution-related categories. Based on synoptic types' weather characteristics and relationships with air pollution concentrations, weather types can be divided into four groups: 1) hot weather, 2) cold weather, 3) air pollution-related, and 3) others, which can facilitate the analysis of synergistic and differential impacts of heat and air pollution on human mortality.

Although air quality was usually "good" in the weather types classified as "other," the elevated mortality within these weather types was still likely caused by air pollution. In order to demonstrate this, days within the weather types "other" were divided into air pollution concentration deciles for each of pollutants; the daily mean mortality rates were then calculated for each of deciles. The results indicated that in the weather types "other," there existed significant relationships between air pollution concentrations and elevated mortality rates.

4.4 *Statistical Downscaling*

The PCA was applied to the domain for all days from 1958 to 2000 for predictors of reanalysis weather elements except for dewpoint and cloud. The downscaling transfer functions, empirical relationships between local-scale predictands and regional-scale predictors, were developed using multiple stepwise regression with an entry and retention significance level of 0.05. There are strong correlations between local-scale predictands and regional-scale predictors, with a model R^2 ≥0.90 for almost all downscaling transfer functions.

It has been known that regression-based downscaling method is problematic for downscaling future extreme events since these phenomena lie at the margins or beyond the range of the calibration dataset (Wilby *et al.*, 2002). To minimize impacts of this shortfall, a variety of tests were attempted and it was found that the use of all principal components selected by stepwise regression rather than the first several components can increase the number of predicted extreme events. Furthermore, for prediction of the station temperatures, the use of upper-air temperatures at 850 and 500 hPa can improve prediction of the extreme events. For instance, at Ottawa the events with temperature >30^{o}C and <-10^{o}C resulted from downscaled CGCM1 historical run increased by 30% after these two modifications were included in the analysis, of which the results were similar to observations.

To evaluate performance of the downscaling models, the data distributions that resulted from CGCM historical runs (1961-2000) were compared with observations/reanalysis data for the same time period. It was shown that data distributions between downscaled historical runs and observations were very similar for all weather elements. The differences between downscaled historical runs and observations should be considered for correction of future elevated mortality assessments (see below).

Using downscaled daily GCM scenarios, hourly values of the scenarios were estimated based on the historical relationships between the hourly observation and its daily mean as well as other weather variables. The regression models showed very strong correlations. For example, the model R^2 were 0.80-0.97 for surface hourly air temperatures, 0.69-0.98 for hourly mean sea-level pressure, and 0.37-0.86 for surface u- and v-winds (28 out of 48 models > 0.6). It was discovered that the downscaling methods used in the study were suitable for downscaling hourly GCM scenarios since data distributions were similar to the observations, but values would change under future climate.

The GCM output of specific humidity was not used in the study since approximately 41-61% of daily mean dew point temperatures calculated from the GCM specific humidity were greater than the GCM outputs of temperatures for the selected stations. Hourly future dew point temperatures were derived from the historical relations between hourly dew point temperature and other hourly weather variables.

The GCM output of total cloud cover was not used in the study because there were no spatial relationships between total cloud cover observations at each of the selected stations and the corresponding principal component scores derived from the NCEP reanalysis cloud cover data field (model R^2<0.1). As a result, hourly future cloud covers were also derived from the historical relations between hourly cloud cover and other hourly weather variables. The results show that the regression models were very strong for both dewpoint and cloud cover.

4.5 *Future Elevated Mortality Rates*

In order to estimate changes in future elevated mortality rates, discriminant function analysis was used to assign each day of future two-time windows (2040-59 and 2070-89) into one of the weather types pre-determined from the observations (1953-2000). Further details on the performance of the discriminant function analysis to identify or predict weather types can be found in a recent publication (Cheng *et al*. 2004).

Following the determination of the weather type for each of future days based on the downscaled GCM scenarios, the future elevated mortality rates were estimated by comparing frequencies of weather types between future climate and historical observations. The results showed that the heat-related mortality would be more than doubled by the 2050s and tripled by the 2080s; and cold-related mortality could dramatically decease in the future. Air pollution-related mortality may be slightly deceased in the study area, given that air quality and weather correlations as well as emissions-driven air quality conditions remain unchanged. Overall the elevated mortality caused by extreme weather and air pollution together could slightly increase, given above the assumptions for air quality conditions. Since these results were dependent only on changes in weather type frequencies, another assessment will be conducted in future using the projected weather types, weather characteristics, and air pollution concentrations.

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