J4.2 SYNOPTIC WEATHER PATTERNS AND MODIFICATION OF THE ASSOCIATION BETWEEN AIR POLLUTION AND HUMAN MORTALITY

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1. ABSTRACT

Daily and seasonal fluctuations in mortality have been positively and significantly associated with ambient concentrations of atmospheric pollution and meteorological variables such as temperature and barometric pressure. However, much less is known about the health risk from atmospheric pollutants in the context of frequently occurring weather patterns. The objective of this study is to assess the relationship between short-term exposure to urban air pollution and all-cause, and cardio-respiratory mortality under typical meteorological conditions.

Concentrations of air pollutants (including carbon monoxide, sulfur dioxide, nitrogen dioxide, ozone and fine particulate matter) and human mortality from non-accidental causes were examined according to typical winter and summer synoptic climatologies in Toronto, Canada, between 1981 and 1999. Air masses were derived using a hybrid spatial synoptic classification procedure associating each day over the 19-year period with one of six different weather types, or a transition between two weather types typical to southern Ontario. Generalized linear models (GLMs) were used to assess the risk of mortality from air pollution within specific air mass type subsets.

Patterns of mortality follow a distinct seasonal pattern with a maximum in winter and a minimum in summer. Average air pollution concentrations were similar in both seasons with the exception of elevated sulfur dioxide levels in winter and elevated ozone levels in summer. Mortality rates and air pollution concentrations vary significantly among air mass types and there is evidence that the effect of air pollution on mortality can be modified according to the presence or absence of specific weather conditions. Typical strategies to control for specific weather variables in the study of air pollution and health effects are effective if the objective is an assessment of overall risk. A synoptic weather modeling strategy has more utility when attempting to discern the modification of air pollution and health associations according to natural variation of weather. These results also provide evidence of a possible interaction between air pollution and warmer than average weather conditions.

2. INTRODUCTION

Numerous epidemiological studies have reported daily and seasonal fluctuations in mortality to be positively and significantly associated with atmospheric pollution and meteorological variables such as temperature and barometric pressure, although much less is known about the health risk from atmospheric pollutants in the context of frequently occurring weather patterns. Typical time-series investigations of health risk from air pollution or from thermal stress will statistically control for potential confounders by including representative variables in regression equations. For example, two studies of the association between air pollution and mortality covering thirty-one North American cities controlled for the confounding effects of weather by including temperature or a temperature-related index in the models (Burnett et al., 1998; Samet et al., 2000). Similarly, investigations of the health effects from thermal stress, such as heat or cold waves, will include some variable to control for the effect of air pollution (O'Neill et al., 2003; Pattenden et al., 2003; Rainham and Tomic, 2003).

Patterns of air pollution dispersion and concentration are generally driven by weather (Flemming, 1996) and variation in anthropogenic emission-related activities. Several studies have shown temperature to positively influence the concentrations of several common urban air pollutants (Gotoh, 1993; Niccum et al., 1995). The potential for air pollution or meteorological variables to confound and/or modify risk estimates of mortality remains uncertain. For example, studies have reported synergistic temperature/air pollution effects on health when temperatures are

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unusually cool (Lebowitz et al., 1973), or warm (Katsouyanni et al., 1993; Wyzga and Lipfert, 1994; Styer et al., 1995; Choi et al., 1997). The limited number of studies and inconsistent results necessitate further research on how the association between air pollution and mortality is affected by certain weather conditions.

Synoptic approaches, as an alternative to traditional descriptive and empiric methods for examining weather, group weather patterns according to similar and frequently occurring meteorological complexes (Kalkstein et al., 1987). Subsequent studies have used synoptic methods to confirm associations between respirable particles and mortality (Pope and Kalkstein, 1996), to estimate the impact of climate change on human health (Kalkstein and Greene, 1997), to aid in the forecast of air pollution episodes (Lam and Cheng, 1998), and to explore air pollution effects on human mortality during extreme weather conditions (Smoyer et al., 2000). Developing knowledge on the role of weather in environment and health relationships may lead to enhanced understanding of the potential health effects arising from global climate change. The spatial synoptic classification process has proven to be very useful in biometeorological applications since organisms generally respond to ambient atmospheric conditions and not just temperature and pressure patterns.

The aim of this study is to evaluate the applicability of a synoptic approach to assess the short term association between air pollution and mortality in Toronto, Canada. Toronto is Canada's largest city, with approximately 4.3 million people in the greater metropolitan area and is situated on the north shore of Lake Ontario (43°40'N). We assess the variability of air pollution and mortality, and also produce estimates of risk to health from ambient air pollution among air mass types typical to winter and summer seasons when weather is most likely to modify the air pollution and health relationship.

3. METHOD

3.1 *Mortality, weather, and air pollution data*

We assembled a nineteen year series consisting of daily counts of non-trauma mortality, weather and air pollution concentration data[†]. Mortality data collected from Statistics Canada were grouped into total (ICD9: <800), cardiorespiratory (ICD9: 390-459; 480-519), and non-cardiorespiratory deaths. Meteorological data used for the development of synoptic air mass categories are distributed by the Meteorological Service of Canada from a station at the Toronto Pearson International Airport, located approximately 15km west of the urban core. The Ontario Ministry of the Environment provided hourly average concentrations of carbon monoxide, nitrogen dioxide, sulphur dioxide, ozone, and fine particles from monitoring sites not influenced by local source pollution. These measurements were averaged to obtain a daily time series of pollution concentrations.

3.2 *Creation of synoptic weather categories*

The spatial synoptic classification (SSC) system is a semi-automated statistical approach designed to classify the complexity of daily weather conditions into one of six distinct categories, or a transitional category which represents a day when one weather category yields to another. To discriminate among weather categories we used values of temperature, dew point, u (east-west) and v (north-south) components of wind, cloud cover, and sea level pressure collected daily at 4, 10, 16 and 22h EST. A detailed explanation of the categorization process can be found elsewhere (Sheridan, 2002).

3.3 *Analysis*

Analysis of the data was conducted in two stages. In the first stage we calculated mean (and standard deviation) values of mortality and air pollution for each of the seven synoptic air mass categories for winter (December-February) and summer (June-August) seasons. Lag effects were examined by evaluating the type of air mass on the day of death, as well as one and two days prior. Limiting the analysis to these observations helps to ameliorate potential bias resulting from selective reporting of lags related to the largest effect estimates and corresponds more closely to the acute nature of atmospheric health risks. Two-tailed *t*-tests were used to ascertain whether particular air masses have atypical values of mortality or pollutant concentrations.

In the second stage of the analysis we explored the potential modification of the association between air pollution and mortality. This involves a relatively standardized approach to the specification of log-linear models with Poisson error to assess the effects of air pollution while accounting for influential temporal trends using a parametric method. Natural splines were used to manage serial autocorrelation in the mortality data and to model various combinations of air pollutants and lag structures. A combination of procedures, including partial autocorrelation plots, a modified Bartlett's Test (to examine residual structures), and Akaike's Information Criterion (AIC), were used to explore the relation between mortality and potential time related confounders. Based on these diagnostics we selected eight degrees of freedom per year for total and cardiorespiratory mortality and six degrees of freedom for all other mortality outcomes for a total of 152*df* and 114*df* respectively over the 19 years of record. We considered parametrically smoothed functions of air pollution for the same day and up to the previous two days, each with between two to six degrees of freedom. Factor variables were also included to control for variation in mortality on different days of the week and during winter and summer holidays.

[†] Abbreviations: CO, carbon monoxide; NO_2, nitrogen dioxide; SO_2, sulphur dioxide; O_3, ozone; $PM_{2.5}$, particulate matter < 2.5 microns in aerodiameter; GLM, generalized linear model; AIC, Akaike's Information Criterion; DM, dry moderate; DP, dry polar; DT, dry tropical; MM, moist moderate, MP, moist polar, MT, moist tropical; TR, transitional; SLP, sea level pressure; T_a, dry-bulb temperature; T_d, dew point temperature.

Separate models were run for each pollutant, within each air mass and by season. The final model formulation has the form below:

$$E[\log(Yi_j)] = a + ns(i_j, df) + dow + ns(ap_j, df) \quad (1)$$

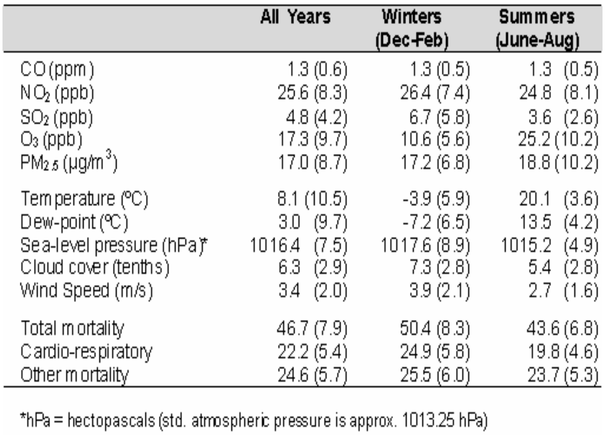
where Yi_j is the number of deaths on day i in air mass j, (i_j) specifies the day in the time series assigned to air mass j, dow is a factor variable to control for day-of-week variability in mortality, ap_j represents the daily air pollution in air mass j, and where the (per year) degrees of freedom (df) specifies the smoothness of the parameter in the model.

The aggregate models were fit using the *glm*( ) function in S-Plus 6.1 software (S-Plus for Windows, Seattle, WA) using a stringent convergence tolerance (1e^{-15}) and a limit of 1000 iterations (Dominici et al., 2002; Ramsey et al., 2003).

4. RESULTS AND DISCUSSION

Concentrations of most air pollutants declined over time, except for ozone which has both increased in concentration and in variability over the nineteen year period. Pollutant concentrations associated with transportation and combustion processes were higher in winter than summer. Fine particle concentrations were slightly elevated in summer and ozone concentrations were 2.5 times higher in summer than in winter. Seasonal variations were also found for all mortality outcomes typically with more deaths in winter than in summer (Table 1).

Table 1 Descriptive statistics for air pollution, weather and mortality data

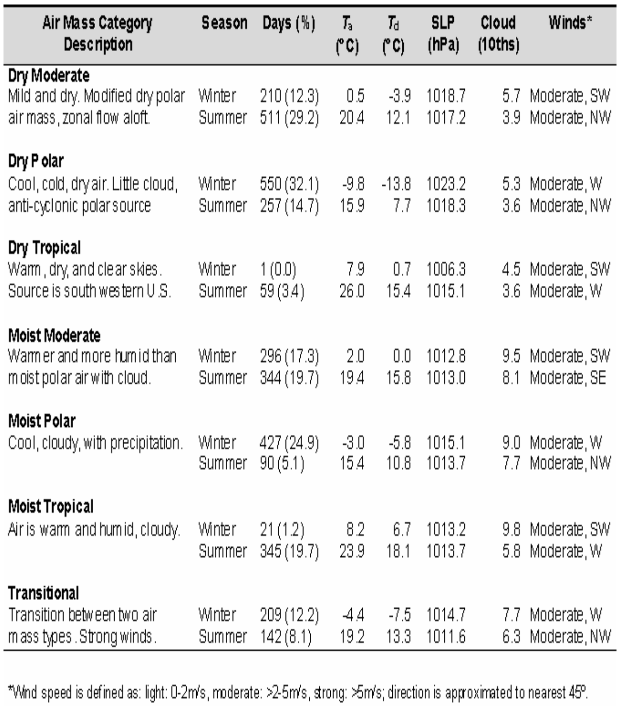


	All Years	Winters (Dec-Feb)	Summers (June-Aug)
CO (ppm)	1.3 (0.6)	1.3 (0.5)	1.3 (0.5)
NO_2 (ppb)	25.6 (8.3)	26.4 (7.4)	24.8 (8.1)
SO_2 (ppb)	4.8 (4.2)	6.7 (5.8)	3.6 (2.6)
O_3 (ppb)	17.3 (9.7)	10.6 (5.6)	25.2 (10.2)
$PM_{2.5}$ (μg/m^3)	17.0 (8.7)	17.2 (6.8)	18.8 (10.2)
Temperature (ºC)	8.1 (10.5)	-3.9 (5.9)	20.1 (3.6)
Dew-point (ºC)	3.0 (9.7)	-7.2 (6.5)	13.5 (4.2)
Sea-level pressure (hPa)*	1016.4 (7.5)	1017.6 (8.9)	1015.2 (4.9)
Cloud cover (tenths)	6.3 (2.9)	7.3 (2.8)	5.4 (2.8)
Wind Speed (m/s)	3.4 (2.0)	3.9 (2.1)	2.7 (1.6)
Total mortality	46.7 (7.9)	50.4 (8.3)	43.6 (6.8)
Cardio-respiratory	22.2 (5.4)	24.9 (5.8)	19.8 (4.6)
Other mortality	24.6 (5.7)	25.5 (6.0)	23.7 (5.3)

*hPa = hectopascals (std. atmospheric pressure is approx. 1013.25 hPa)

Table 2 presents the results of the spatial synoptic classification of meteorological data for Toronto in winter and summer and shows the usefulness of the synoptic approach for investigating all of the variables concurrently. The synoptic approach permits the detection of typical conditions associated with dominant temperatures or ranges in pressure.

Table 2 Meteorological composition of winter and summer air mass types



Air Mass Category Description	Season	Days (%)	T_a (°C)	T_d (°C)	SLP (hPa)	Cloud (10ths)	Winds*
Dry Moderate							
Mild and dry. Modified dry polar	Winter	210 (12.3)	0.5	-3.9	1018.7	5.7	Moderate, SW
air mass, zonal flow aloft.	Summer	511 (29.2)	20.4	12.1	1017.2	3.9	Moderate, NW
Dry Polar							
Cool, cold, dry air. Little cloud,	Winter	550 (32.1)	-9.8	-13.8	1023.2	5.3	Moderate, W
anti-cyclonic polar source	Summer	257 (14.7)	15.9	7.7	1018.3	3.6	Moderate, NW
Dry Tropical							
Warm, dry, and clear skies.	Winter	1 (0.0)	7.9	0.7	1006.3	4.5	Moderate, SW
Source is south western U.S.	Summer	59 (3.4)	26.0	15.4	1015.1	3.6	Moderate, W
Moist Moderate							
Warmer and more humid than	Winter	296 (17.3)	2.0	0.0	1012.8	9.5	Moderate, SW
moist polar air with cloud.	Summer	344 (19.7)	19.4	15.8	1013.0	8.1	Moderate, SE
Moist Polar							
Cool, cloudy, with precipitation.	Winter	427 (24.9)	-3.0	-5.8	1015.1	9.0	Moderate, W
	Summer	90 (5.1)	15.4	10.8	1013.7	7.7	Moderate, NW
Moist Tropical							
Air is warm and humid, cloudy.	Winter	21 (1.2)	8.2	6.7	1013.2	9.8	Moderate, SW
	Summer	345 (19.7)	23.9	18.1	1013.7	5.8	Moderate, W
Transitional							
Transition between two air	Winter	209 (12.2)	-4.4	-7.5	1014.7	7.7	Moderate, W
mass types. Strong winds.	Summer	142 (8.1)	19.2	13.3	1011.6	6.3	Moderate, NW

*Wind speed is defined as: light: 0-2m/s, moderate: >2-5m/s, strong: >5m/s; direction is approximated to nearest 45º.

For example, most winters are characterized by a dry polar air mass (32% of all winter days) and distinguished by cold, dry air, northerly winds and little to no cloud cover suggesting a dominant high pressure system with northern Canadian origins. Typical weather characteristics and large-scale circulation patterns may also be construed from other synoptic categories thus providing a holistic description of predominant conditions.

Results from the first stage of the analysis using spatial synoptic categories to investigate variability in air pollution concentrations and mortality are summarized in Table 3. Mean values of air pollution and mortality from one air mass that are significantly different (higher or lower) from average values of the remaining air masses combined are in bold type.

In winter the MP air mass, typically resulting in cloudy, windy and wet conditions, had consistently less air pollution than other air masses. Pollutants such as NO_2 and SO_2 that are associated with transportation and energy production sources were higher during DM air masses. Elevated O_3 concentrations occurred with the presence of DP air masses which are characteristically cool, sunny and calm, all excellent conditions for the formation of a photoreactive chemical. Rates of mortality remained relatively constant among air masses. However, it is notable that the coldest DP air mass had significantly lower mortality when compared to other air masses, and that mortality was significantly elevated during transition (TR) days characterized by variable, windy weather, typical of frontal passages. These results contrast

Table 3 Average values of air pollution and mortality by air mass type (significant values in bold).

	Dry Moderate	Dry Polar	Dry Tropical	Moist Moderate	Moist Polar	Moist Tropical	Transition
				Winter Season			
Mean Air Pollution (95% C.I.)							
CO (ppm)	1.35 ± 0.09	**1.24 ± 0.04**ˇ	NC	**1.44 ± 0.61**ˆ	**1.23 ± 0.04**ˇ	**1.83 ± 0.50**ˆ	**1.14 ± 0.05**ˇ
NO_2 (ppb)	**29.2 ± 1.1**ˆ	26.3 ± 0.6	NC	27.1 ± 0.8	**25.5 ± 0.6**ˇ	27.4 ± 3.2	**24.3 ± 1.0**ˇ
SO_2 (ppb)	**8.6 ± 0.8**ˆ	6.6 ± 0.5	NC	7.1 ± 0.5	**5.9 ± 0.5**ˇ	7.8 ± 2.2	6.4 ± 0.7
O_3 (ppb)	10.0 ± 0.7	**13.1 ± 0.4**ˆ	NC	**6.9 ± 0.5**ˇ	**9.9 ± 0.5**ˇ	**6.0 ± 2.3**ˇ	**12.2 ± 0.7**ˆ
$PM_{2.5}$ (μg/m^3)	17.0 ± 1.0	17.5 ± 0.5	NC	17.1 ± 0.8	17.5 ± 0.6	16.5 ± 3.6	16.7 ± 1.0
Mean Mortality* and Lags (95% C.I.)							
Total	50.3 ± 1.1	**49.6 ± 0.7**ˇ	NC	50.7 ± 1.0	50.3 ± 0.8	48.7 ± 3.4	**52.3 ± 1.1**ˆ
Lag1	51.3 ± 1.2	**49.7 ± 0.7**ˇ	NC	50.8 ± 1.0	50.0 ± 0.8	48.7 ± 3.0	**51.7 ± 1.1**ˆ
Lag2	51.0 ± 1.1	50.4 ± 0.7	NC	50.1 ± 1.1	50.0 ± 0.7	48.7 ± 3.9	51.0 ± 1.1
Cardioresp	24.5 ± 0.8	24.7 ± 0.4	NC	25.3 ± 0.7	24.3 ± 0.6	24.5 ± 3.1	26.1 ± 0.8
Lag1	25.0 ± 0.8	24.8 ± 0.5	NC	25.2 ± 0.7	24.4 ± 0.7	24.7 ± 2.4	25.3 ± 0.8
Lag2	24.8 ± 0.8	25.1 ± 0.5	NC	24.6 ± 0.7	24.5 ± 0.5	25.5 ± 2.3	25.3 ± 0.8
Other	25.8 ± 0.8	**24.9 ± 0.5**ˇ	NC	25.4 ± 0.7	26.0 ± 0.5	24.1 ± 3.1	26.2 ± 0.8
Lag1	26.4 ± 0.9	**24.8 ± 0.5**ˇ	NC	25.6 ± 0.7	25.6 ± 0.6	24.0 ± 2.4	**26.4 ± 0.8**ˆ
Lag2	26.2 ± 0.9	25.3 ± 0.5	NC	25.5 ± 0.7	25.5 ± 0.5	23.3 ± 2.6	25.7 ± 0.8
				Summer Season			
Mean Air Pollution (95% C.I.)							
CO (ppm)	1.28 ± 0.06	**1.18 ± 0.05**ˇ	1.37 ± 0.16	**1.37 ± 0.06**ˆ	1.40 ± 0.12	1.30 ± 0.04	**1.15 ± 0.06**ˇ
NO_2 (ppb)	**25.7 ± 0.7**ˆ	**20.3 ± 0.8**ˇ	**32.1 ± 2.7**ˆ	25.6 ± 1.1	**21.7 ± 1.6**ˇ	**27.1 ± 0.8**ˆ	**21.5 ± 1.1**ˇ
SO_2 (ppb)	3.8 ± 0.2	**2.5 ± 0.2**ˇ	**6.1 ± 0.8**ˆ	**3.2 ± 0.3**ˇ	**2.6 ± 0.5**ˇ	**4.6 ± 0.2**ˆ	3.5 ± 0.4
O_3 (ppb)	24.6 ± 0.6	**17.8 ± 0.6**ˇ	**43.5 ± 2.9**ˆ	**23.1 ± 1.0**ˇ	**16.0 ± 1.1**ˇ	**33.7 ± 2.0**ˆ	24.0 ± 1.4
$PM_{2.5}$ (μg/m^3)	18.4 ± 0.9	19.0 ± 1.2	18.5 ± 2.4	19.2 ± 1.2	17.5 ± 2.0	19.8 ± 1.1	17.6 ± 1.5
Mean Mortality* and Lags (95% C.I.)							
Total	43.2 ± 0.4	42.9 ± 0.9	**46.0 ± 2.1**ˆ	43.3 ± 0.7	42.7 ± 1.4	**44.8 ± 0.7**ˆ	42.9 ± 1.0
Lag1	43.7 ± 0.5	42.7 ± 0.8	**45.6 ± 1.9**ˆ	42.9 ± 0.7	43.2 ± 1.5	**44.6 ± 0.7**ˆ	43.1 ± 1.1
Lag2	43.9 ± 0.6	43.5 ± 0.8	45.1 ± 0.4	42.9 ± 0.6	41.4 ± 1.5	44.1 ± 0.2	43.5 ± 1.1
Cardioresp.	19.5 ± 0.4	19.7 ± 0.6	**22.1 ± 1.2**ˆ	19.7 ± 0.3	20.1 ± 0.9	20.2± 0.5	20.0 ± 0.8
Lag1	19.7 ± 0.4	19.8 ± 0.6	**21.4 ± 1.3**ˆ	19.7 ± 0.4	20.0 ± 1.0	20.0 ± 0.5	19.5 ± 0.7
Lag2	19.9 ± 0.4	20.2 ± 0.6	20.7 ± 1.3	19.5 ± 0.4	19.7 ± 1.0	19.8 ± 0.5	19.8 ± 0.8
Other	23.7 ± 0.5	23.2 ± 0.7	24.8 ± 1.6	23.7 ± 0.5	**22.6 ± 1.0**ˇ	**24.6 ± 0.6**ˆ	**22.9 ± 0.7**ˇ
Lag1	23.9 ± 0.5	22.9 ± 0.6	24.2 ± 1.3	23.2 ± 0.5	23.2 ± 1.2	**24.6 ± 0.6**ˆ	23.6 ± 0.8
Lag2	24.0 ± 0.5	23.3 ± 0.6	24.4 ± 1.3	23.4 ± 0.6	**21.7 ± 0.2**ˇ	**24.3 ± 0.5**ˆ	23.7 ± 0.9

Bolded values indicate value for synoptic category is significantly statistically different ($p < 0.05$) than the mean according to a two-tailed *t*-test, ˆ = mean is greater than comparison categories , ˇ = mean is less than comparison categories; NC = no comparison due to only one observation.

previous research that identified increased winter mortality on days with DP air masses among 44 U.S. cities (Kalkstein and Greene, 1997). Interestingly, the DP and TR air masses had relatively lower pollutant concentrations, significantly so in the TR air mass, yet had very different rates of mortality. More daily deaths occurred in the TR category than in any other air mass. It seems that in winter, air pollutants appear to be secondary to weather in contributing to increased rates of mortality.

In summer mean rates of mortality and concentrations of air pollution varied significantly among air mass types and there was better concordance between higher concentrations of air pollution and increased mortality. Two air masses were particularly oppressive in terms of increased mortality and higher than average pollutant concentrations. The DT and MT air mass categories, comprising approximately 23% of all summer days, were the warmest and also possessed the highest concentrations of air pollution. The DT air mass, which is very hot and dry, possessed air pollution concentrations well above values inherent to other air masses. This finding differs from previous research where the hottest air mass was characterized by relatively average pollutant levels (Smoyer et al., 2000). In contrast significantly lower pollution concentrations were observed in the DP and MP air mass categories, conditions characterized by relatively cool temperatures, and cloudy conditions in the latter category. Rates of mortality were also lower for the DP and MP air masses but not significantly.

Table 4 (winter) and Table 5 (summer) summarize the results from the second stage of the analysis where log-linear regression models were used to assess the association between air pollution and mortality within synoptic weather categories. These tables illustrate the relative risk (RR) and 95% confidence intervals of mortality based on a per unit change of each pollutant. For winter there is little evidence of a relationship between air pollution and mortality according to regression results that included all days in the season. Only CO was positively, significantly associated with total mortality (RR=1.024). Previous research has alluded to the difficulty in determining high risk winter air masses (Kalkstein and Greene, 1997). However, there is evidence from Table 4 that the MT air mass shows consistently strong associations between cardiorespiratory and non-cardiorespiratory mortality and CO (RR=1.266 to 1.812), NO_2 (RR=1.027 to 1.044), as well as fine particles (RR=1.123 to 1.248).

Although the presence of an oppressive winter air mass (MT) is somewhat unusual, it is difficult to ascertain why pollutant effects were observed for cardiorespiratory and non-cardiorespiratory deaths but not for all deaths combined. The results may also be spurious due to the small number of days included in the regression models and the potential for exposure misclassification since most people are confined to indoor environments in the winter season. For example, there were no clear patterns in pollutant and mortality associations for other winter synoptic situations. Also, pollutant/mortality associations were strongest during synoptic situations characterized by lower mean daily mortality. This result suggests that the synoptic approach is useful for identifying whether air pollution or weather increases risk of mortality.

The role of anticyclonic air masses, in this case dominated by relatively warmer, moist conditions, has previously been implicated in excess rates of respiratory admissions and deaths from ischemic heart disease (McGregor et al., 1999), increases in overall mortality (Kalkstein and Greene, 1997) as well as sustained pollutant levels (Curson, 1996). Laschewski and Jendritzky (2002) found that the sudden moderation of cold thermal conditions in winter was related to increased mortality rates and that re-cooling would lead to reduced physiological strain. The apparent susceptibility to air pollution during unusually moist and mild conditions in winter may be related to weather/pollutant interactions and the ability of a person's thermal regulatory system to adapt to sudden changes in weather after acclimatization to typical winter conditions. In addition, a potential increase in the frequency of MT days in the winter season may counter predictions of winter mortality reductions from climate warming.

Relative risks of mortality for each pollutant over the summer season and by synoptic air mass category are given in Table 5. For models that included all summer days, positive associations were observed between total mortality and CO (RR=1.040) and SO_2 (RR=1.004). Cardiorespiratory mortality was positively, significantly associated with SO_2 (RR=1.005) and O_3 (RR=1.002) although these effects are quite small. Mortality from non-cardiorespiratory causes was also positively and moderately associated with CO (RR=1.057). These results are consistent with previous risk estimates of the association between air pollution and mortality for Toronto with CO having the largest effect on daily fluctuations of mortality (Burnett et al., 1997).

All but the TR air mass categories had positive, significant associations between air pollution and mortality. Associations were most consistent for the DM category. Relative risks for total and non-cardiorespiratory mortality were 1.058 and 1.103 for CO, 1.003 and 1.005 for NO_2, and 1.012 and 1.021 for SO_2. Ozone concentrations were significantly associated (RR=1.003) with both cardiorespiratory and non-cardiorespiratory deaths. Average concentrations of pollutants and mortality were not significantly different in this category than seasonal averages. DM air masses accounted for almost 30% of all summer days and had comfortable weather conditions characterized by persistent high pressure systems, warm temperatures and sunny conditions. Relative risks were stronger for particulates and ozone in the hot, dry DT air mass category. All mortality categories were significantly associated with $PM_{2.5}$ (RR=1.016 to 1.017) and total and cardiorespiratory mortality were associated with O_3 (RR=1.010 and 1.014). We also observed increased risk or mortality in a few of the other air masses. Risk of mortality from CO was significant for the DP (RR=1.208 for non-cardiorespiratory mortality), MM (RR=1.094 and 1.099 for total and cardiorespiratory mortality) and MP (RR=1.406 for cardiorespiratory mortality) air masses. Risk of mortality from NO_2 was significant among MM (RR=1.003 for total mortality) and MT (RR=1.005 for cardiorespiratory mortality) air mass categories. Fine particles were associated with non-cardiorespiratory mortality (RR=1.004) on days with MM air masses present.

The results from the summer within air mass category regression help to delineate instances where pollutant and mortality associations are not modified by weather conditions or possibly where the same associations may be intensified. For example, the DM and MM air masses had more consistent associations between more types of air pollution and mortality than other air mass categories and account for almost 50% of all summer days. Average concentrations of pollutants and mean mortality rates are not significantly different in these categories when compared to values among all other categories. Thus it is unlikely that weather conditions, such as temperature or sudden changes in pressure, would account for much of the variability in mortality from one day to the next in the DM and MM air mass categories. Accuracy of risk estimates of the association between mortality and air pollution may actually be improved since there is less possibility for weather conditions to modify and/or confound model estimates.

Table 4 Relative risk of mortality from air pollution among winter synoptic weather categories

	Air Pollutant				
	CO	**NO_2**	**SO_2**	**$PM_{2.5}$**	**O_3**
Winter					
Total	**1.024 (1.005–1.044)†**	1.001 (1.000–1.002)†	1.001 (1.000–1.003)†	0.998 (0.997–1.000)‡	0.998 (0.997–1.000)†
Cardioresp	0.971 (0.945–0.997)	0.998 (0.996–0.999)	0.998 (0.997–1.000)	0.998 (0.996–1.000)‡	1.003 (1.000–1.005)
Other	1.026 (0.999–1.055)	1.002 (1.000–1.003)†	1.002 (1.000–1.004)†	0.998 (0.996–1.000)‡	0.998 (0.995–1.000)†
Dry Moderate (DM), n = 210					
Total	1.058 (0.957–1.171)†	**1.006 (1.001–1.012)†**	1.003 (0.996–1.009)†	1.001 (0.996–1.007)†	0.993 (0.986–0.999)†
Cardioresp	1.117 (0.986–1.266)†	1.006 (1.000–1.013)†	1.002 (0.993–1.011)†	1.005 (0.998–1.011)†	0.992 (0.983–1.001)†
Other	1.103 (0.995–1.223)‡	1.005 (0.996–1.013)†	1.003 (0.993–1.013)†	0.997 (0.989–1.006)	0.990 (0.980–0.999)†
Dry Polar (DP), n = 550					
Total	1.029 (0.989–1.072)†	1.001 (0.999–1.003)†	1.002 (1.000–1.005)†	0.998 (0.995–1.001)‡	0.998 (0.994–1.001)†
Cardioresp	1.033 (0.977–1.093)†	0.998 (0.995–1.000)	1.002 (0.999–1.006)†	0.995 (0.991–0.999)‡	1.004 (1.000–1.009)
Other	1.024 (0.965–1.085)†	1.002 (0.999–1.005)†	1.002 (0.999–1.005)	1.002 (0.998–1.005)†	0.998 (0.993–1.002)†
Dry Tropical (DT), n = 1					
One observation only.					
Moist Moderate (MM), n = 296					
Total	0.992 (0.929–1.059)†	0.996 (0.992–0.999)	0.995 (0.990–1.000)	0.998 (0.993–1.002)‡	0.997 (0.992–1.002)‡
Cardioresp	**1.084 (1.007–1.166)‡**	0.993 (0.987–0.999)	0.991 (0.983–0.998)	1.003 (0.995–1.010)†	0.992 (0.984–1.000)†
Other	0.922 (0.857–0.993)‡	0.997 (0.992–1.002)‡	0.999 (0.993–1.005)‡	0.997 (0.991–1.004)†	1.005 (0.998–1.013)†
Moist Polar (MP), n = 427					
Total	**1.048 (1.002–1.096)†**	0.998 (0.995–1.001)‡	0.997 (0.993–1.000)‡	1.001 (0.998–1.005)†	1.003 (1.000–1.007)‡
Cardioresp	0.959 (0.892–1.032)	0.998 (0.993–1.002)†	0.998 (0.992–1.003)	1.002 (0.997–1.007)‡	1.003 (0.998–1.009)‡
Other	**1.071 (1.008–1.139)†**	0.998 (0.994–1.002)‡	0.995 (0.990–1.000)‡	1.003 (0.999–1.007)	1.004 (0.999–1.010)
Moist Tropical (MT), n = 21					
Total	1.069 (0.932–1.227)	1.012 (0.986–1.039)	0.972 (0.936–1.011)†	1.007 (0.965–1.203)	0.972 (0.994–1.000)
Cardioresp	**1.812 (1.420–2.311)‡**	**1.027 (1.006–1.048)‡**	1.026 (0.998–1.055)‡	**1.123 (1.031–1.224)‡**	0.975 (0.948–1.003)‡
Other	**1.266 (1.099–1.460)**	**1.044 (1.016–1.074)**	0.955 (0.906–1.008)‡	**1.248 (1.123–1.387)**	0.894 (0.860–0.929)†
Transition (TR), n = 209					
Total	1.088 (0.994–1.190)‡	**1.005 (1.001–1.009)‡**	1.005 (1.000–1.011)†	1.003 (0.996–1.009)†	0.996 (0.991–1.001)†
Cardioresp	0.912 (0.815–1.021)	0.995 (0.989–1.000)	1.007 (0.999–1.015)†	0.996 (0.987–1.004)	0.992 (0.985–1.000)†
Other	1.083 (0.965–1.214)‡	1.004 (0.999–1.010)‡	1.005 (0.997–1.012)†	0.997 (0.990–1.004)	0.996 (0.989–1.003)‡

Bolded values indicate positive, significant associations; † = 1-day lag; ‡ = two-day lag;

Table 5 Relative risk of mortality from air pollution among summer synoptic weather categories

	Air Pollutant				
	CO	**NO_2**	**SO_2**	**$PM_{2.5}$**	**O_3**
Summer					
Total	**1.040 (1.015–1.065)†**	1.001 (1.000–1.002)†	**1.004 (1.001–1.007)†**	1.000 (1.000–1.001)	1.001 (1.000–1.001)‡
Cardioresp	1.021 (0.986–1.057)‡	1.001 (1.000–1.003)‡	**1.005 (1.001–1.010)‡**	1.001 (1.000–1.002)	**1.002 (1.001–1.003)‡**
Other	**1.057 (1.021–1.094)†**	1.002 (1.000–1.003)†	1.005 (1.000–1.010)†	1.001 (1.000–1.002)	0.999 (0.998–1.001)‡
Dry Moderate (DM), n = 511					
Total	**1.058 (1.006–1.112)†**	**1.003 (1.001–1.005)†**	**1.012 (1.005–1.019)†**	1.001 (0.999–1.002)‡	1.002 (1.000–1.003)
Cardioresp	1.030 (0.955–1.110)†	1.002 (0.999–1.005)†	1.004 (0.994–1.014)‡	1.002 (0.999–1.004)‡	**1.003 (1.001–1.006)‡**
Other	**1.103 (1.027–1.185)†**	**1.005 (1.002–1.008)†**	**1.021 (1.011–1.031)†**	0.999 (0.997–1.002)	**1.003 (1.001–1.006)**
Dry Polar (DP), n = 257					
Total	1.082 (0.987–1.185)†	1.002 (0.998–1.006)†	1.013 (0.997–1.029)†	1.002 (0.999–1.005)‡	1.002 (0.999–1.006)†
Cardioresp	0.942 (0.840–1.055)	0.996 (0.989–1.003)	0.976 (0.951–1.001)	0.996 (0.991–1.000)	1.003 (0.999–1.007)‡
Other	**1.208 (1.079–1.352)†**	1.005 (0.999–1.010)†	1.018 (0.997–1.040)†	1.003 (0.999–1.007)‡	1.006 (0.998–1.014)
Dry Tropical (DT), n = 59					
Total	1.236 (0.911–1.678)‡	0.995 (0.986–1.005)†	1.006 (0.978–1.035)‡	**1.016 (1.006–1.027)**	**1.010 (1.002–1.019)**
Cardioresp	1.410 (0.965–2.059)‡	0.994 (0.982–1.006)†	0.989 (0.959–1.020)†	**1.017 (1.005–1.030)‡**	**1.014 (1.003–1.025)**
Other	1.099 (0.750–1.609)‡	0.997 (0.985–1.009)†	1.006 (0.976–1.037)	**1.017 (1.003–1.031)**	1.007 (0.996–1.019)
Moist Moderate (MM), n = 344					
Total	**1.094 (1.032–1.159)**	**1.003 (1.001–1.006)**	0.998 (0.990–1.007)‡	1.002 (1.000–1.004)‡	0.998 (0.995–1.001)
Cardioresp	**1.099 (1.009–1.198)**	1.004 (0.999–1.008)	1.004 (0.991–1.016)‡	1.003 (0.999–1.006)‡	1.003 (1.000–1.006)†
Other	1.078 (0.988–1.177)	1.003 (0.999–1.007)	0.995 (0.983–1.007)‡	**1.004 (1.001–1.006)**	0.997 (0.993–1.001)
Moist Polar (MP), n = 90					
Total	1.108 (0.924–1.327)	1.009 (0.998–1.020)‡	1.015 (0.982–1.049)†	1.005 (0.998–1.011)†	1.004 (0.997–1.012)‡
Cardioresp	**1.406 (1.103–1.793)**	1.015 (0.998–1.032)‡	1.014 (0.963–1.068)†	1.008 (0.997–1.018)	1.002 (0.991–1.014)‡
Other	0.874 (0.706–1.083)	1.001 (0.990–1.012)‡	1.015 (0.974–1.057)‡	1.003 (0.995–1.011)†	1.010 (0.996–1.025)
Moist Tropical (MT), n = 345					
Total	1.040 (0.968–1.119)‡	1.001 (0.998–1.004)‡	1.002 (0.995–1.010)†	0.999 (0.997–1.001)‡	0.999 (0.997–1.001)
Cardioresp	1.089 (0.973–1.218)‡	**1.005 (1.001–1.010)‡**	1.010 (0.998–1.022)‡	0.996 (0.993–1.000)‡	0.996 (0.993–1.000)
Other	1.055 (0.959–1.160)	0.997 (0.994–1.001)‡	0.955 (0.985–1.005)‡	0.998 (0.995–1.001)†	0.999 (0.996–1.002)‡
Transition (TR), n = 142					
Total	1.157 (0.919–1.456)	1.005 (0.998–1.012)	1.021 (0.999–1.043)	1.005 (0.996–1.014)†	0.993 (0.986–1.000)†
Cardioresp	1.137 (0.820–1.576)	1.004 (0.994–1.014)	1.031 (0.982–1.084)‡	1.007 (0.994–1.020)†	0.989 (0.980–0.999)†
Other	1.103 (0.886–1.373)	1.004 (0.997–1.011)	1.018 (0.996–1.040)	1.002 (0.996–1.008)‡	1.007 (1.000–1.013)

Bolded values indicate positive, significant associations; † = 1-day lag; ‡ = two-day lag

Of primary interest in this study is the role of weather conditions in the modification of air pollution and mortality associations. DT and MT air mass categories had the greatest mean concentrations of air pollution and the highest rates of daily mortality when compared with other air masses. Results from the regression models, however, indicate that pollutant/mortality associations are significant only for fine particles and ozone in the DT air mass, and NO_2 in the MT air mass. Studies have shown that daily variations in ozone and respirable particulates are also associated with daily mortality rates even after adjustment for temperature (Hoek et al., 2000; Katsouyanni et al., 2001). We hypothesize that there is likely an interaction between air pollution and some aspect of weather, most likely temperature, or possibly that air pollutants interact among themselves to create more potent mixtures. Previous research has found interactions between ozone and PM_{10} (Krzyzanowski et al., 1992), and there is evidence from epidemiological investigations that interactions occur between relatively high concentrations of air pollution and high temperatures (Katsouyanni et al., 1993; 2001). Regression results with additional terms to represent potential interactions between temperature and pollutant variables were not significant and not always positive (results not shown) possibly due to reduced statistical power to detect associations. Risk estimates from the MT air mass indicate that air pollution is likely secondary to temperature extremes as the reason for elevated rates of mortality (Table 3).

It is not completely clear why associations between air pollution and daily mortality were stronger in DT than MT air mass categories even though both categories had highly elevated levels of most pollutants. Dry bulb temperatures in the DT air mass were on average 2°C warmer than in the MT air mass. Another important difference may be related to dew point temperatures, a lack of night-time cooling and the effect of increased humidity on normal physiological function. Heat wave research has identified smaller diurnal temperature ranges as a risk factor for increased mortality (Smoyer-Tomic et al., 2003). The high humidity associated with MT air may lessen the body's ability to regulate evaporative heat loss by perspiration and vasodilatation or potentially influence the transport of fine particles. On DT days, however, gradients in vapour pressure can lead to situations of dehydration and hyperthermal conditions due to insufficient perspiration from increased evaporation (Jendritzky, 1991).

5. CONCLUSIONS

The objective of this study was to evaluate the potential for synoptic weather patterns to modify the relationship between ambient air pollutants and mortality for winter and summer in Toronto, Canada. A spatial synoptic climatological procedure was used to develop a daily series of air masses for which values of air pollution and mortality can be calculated. These air masses are essentially a simplified representation of atmospheric conditions where each air mass is a delineation of specific meteorological characteristics.

Prevailing patterns of synoptic air masses were identified for winter and summer seasons as well as the average air pollution and human mortality for each category. In winter the coldest air masses were characterized by low pollutant concentrations and reduced winter mortality confirming previous research that day-to-day variation in mortality is probably associated with additional factors related to the winter season rather than with colder temperatures (Davis et al., 2004). The maritime tropical (MT) winter air mass displayed consistent results with respect to associations between air pollution and mortality. Relative risks were much stronger when compared with other air mass types, especially for CO and $PM_{2.5}$ concentrations. Comparable research has also identified the connection between winter season anticyclonic, humid air masses and human health effects (McGregor et al., 1999). The primary source of carbon monoxide (which is also composed of ultrafine particles) in Toronto is gasoline-powered motor vehicles (Campbell et al., 1995). The pathophysiologic mechanisms of CO and fine particles are well known (NRC, 2004). Furthermore, humid conditions have been shown to influence the size, transport, and the biological effects of particles (Flemming, 1996).

Application of synoptic climatology to the summer season revealed two hot, polluted and particularly oppressive air mass categories (DT and MT) as well as two categories with significantly better air quality (DP and MP). Our results reveal the effectiveness of the synoptic approach in capturing the variability of air pollution concentrations and the corresponding meteorological conditions. Significant, positive associations between most pollutants and mortality were found for days belonging to the DM air mass. Given the average summer weather conditions that characterize this air mass, it is reasonable to conclude that stable, comfortable weather conditions do little to modify pollutant/mortality associations, even at relatively low ambient pollutant concentrations. Results for the most polluted and oppressive air masses (DT and MT) were quite dissimilar where ozone and fine particle associations with mortality were significant in the former and not in the latter category. Although there appears to be modification of the effect of air pollution on mortality by the presence (or absence) of specific air masses, the importance of specific weather variables, such as temperature, in the determination of health outcomes was not ascertained. Numerous epidemiological studies have observed an increase in risk of mortality associated with hot, humid weather conditions (Basu and Samet, 2002) and some have suggested that interactions between temperature and air pollutants may produce synergistic effects on health (Smoyer et al., 2000; Katsouyanni et al., 2001).

Overall, the findings from this investigation strengthen the case that subtle changes in meteorological composition can alter the strength of pollutant associations with health outcomes, especially in the summer season. Although there does not appear to be any systematic patterning of modification, variation in pollutant concentrations seems dependent on the type of synoptic category present. This finding corresponds well to evaluations of air quality according to specific weather types (Flemming, 1996; Leighton and Spark, 1997; Cheng and Lam, 2000). There is a need for additional research to improve our understanding of the potential for the totality of atmospheric conditions to impact human health. The results presented here should signal health and environmental policy makers to consider the application of the synoptic approach to reveal atmospheric situations harmful to human well-being. Potentially harmful synoptic situations can be identified in advance and appropriate warnings or prevention activities could be enacted to ameliorate human health impacts.

6. REFERENCES

Basu, R. and J.M. Samet, 2002: Relation between elevated ambient temperature and mortality: a review of the epidemiologic evidence. *Epidemiol. Rev.*, **24**, 190-202.

Burnett, R.T., Çakmak, S., Brook, J., 1998: The effect of the urban ambient air pollution mix on daily mortality rates in 11 Canadian cities. *Can J. Pub. Health*, **89**, 152-156.

Campbell, M.E., Benson, B.A. and M.A. Muir, 1995: Urban air quality and human health: a Toronto perspective. *Can. J. Pub. Health*, **86**, 351-357.

Cheng, S. and K.C. Lam, 2000: Synoptic typing and its application to the assessment of climatic impact on concentrations of sulphur dioxide and nitrogen oxides in Hong Kong. *Atmos. Environ.*, **34**, 585-594.

Choi, K.-S., Inoue, S., Shinozaki, R., 1997: Air pollution, temperature, and regional differences in lung cancer mortality in Japan. *Arch. of Env. Health*, **52**, 160-168.

Curson, P., 1996: Human health, climate and climate change: an Australian perspective. In: T. Giambelluca and A. Henderson-Sellers, (Eds.), *Climate change: developing southern hemisphere perspectives*, (p. 475). Chichester: Wiley.

Davis, R.E., Knappenberger, P.C., Michaels, P.J. and W.N. Novicoff, 2004: Seasonality of climate-human mortality relationships in US cities and impacts of climate change. *Clim. Res.*, **26**, 61-76.

Flemming, G., 1996: The importance of air quality in human biometeorology. *Int. J. Biometeorol.*, **39**, 192-196.

Gotoh, T., 1993: Relation between heat islands and NO_2 pollution in some Japanese cities. *Atmos. Environ.*, **27B**, 121-128.

Hoek, G., Brunekreef, B., Verhoeff, A., van Wijnen, J. and P. Fischer, 2000: Daily mortality and air pollution in the Netherlands. *J. Air Waste Man. Assoc.*, **50**, 1380-1389.

Jendritzky, G., 1991: Selected questions of topical interest in human bioclimatology. *Int. J. Biometeorol.*, **35**, 139-150.

Kalkstein, L.S., Tan, G. and J. Skindlov, 1987: An evaluation of objective clustering procedures for use in synoptic climatological classification. *J. Clim. App. Meteorol.*, **26**, 717-730.

Kalkstein, L.S. and J.S. Greene, 1997: An evaluation of climate/mortality relationships in large U.S. cities and possible impacts of climate change. *Environ. Health Perspect.*, **105**, 84-93.

Katsouyanni, K., Pantazopoulou, A., Touloumi, G., et al., 1993: Evidence for interaction between air pollution and high temperature in the causation of excess mortality. *Arch. of Env. Health*, **48**, 235-242.

Katsouyanni, K., Touloumi, G., Samoli, E., et al., 2001: Confounding and effect modification in the short-term effects of ambient particles on total mortality: results from 29 European cities within the APHEA2 project. *Epidemiology*, **12**, 521-531.

Krzyzanowski, M., Quakenboss, J.J. and M.D. Lebowitz, 1992: Relation of peak expiratory flow rates and symptoms to ambient ozone. *Arch. Environ. Health*, **46**, 262-270.

Laschewski, G. and G. Jendritzky, 2002: Effects on the thermal environment on human health: an investigation of 30 years of daily mortality data from SW Germany. *Clim. Res.*, **21**, 91-103.

Lam, K-C. and S. Cheng, 1998: A synoptic climatological approach to forecast concentrations of sulphur dioxide and nitrogen oxides in Hong Kong. *Environ. Pollution*, **101**, 183-191.

Lebowitz, M.D., Cassell, E.J., and J.D. McCarroll, 1973: Health and the urban environment. XV. Acute respiratory episodes as reaction by sensitive individuals to air pollution and weather. *Environ. Res.*, **5**, 135-141.

Leighton, R.M. and E. Spark, 1997: Relationship between synoptic climatology and pollution events in Sydney. *Int. J. Biometeorol.*, **41**, 76-89.

McGregor, G.R., Walters, S., and J. Wordley, 1999: Daily hospital respiratory admissions and winter air mass types, Birmingham, UK. *Int. J. Biometeorol.*, **43**, 21-30.

NRC (National Research Council), 2004: *Research priorities for airborne particulate matter: IV. Continuing research progress*, (pp. 256). Committee on Research Priorities for Airborne Particulate Matter, National Research Council. Washington, D.C.: National Academies Press.

Niccum, E.M., Lehrman, D.E. and W.R. Knuth, 1995: The influence of meteorology on the air quality in the San Luis Obispo County-South-western San Joaquin Valley region for 3-6 August 1990. *J. Appl. Meteorol.*, **34**, 1834-1847.

O'Neill, M.S., Zanobetti, A. and J. Schwartz, 2003: Modifiers of the temperature and mortality association in seven US cities. *Am. J. Epi.*, **157**, 1074-1082.

Pattenden, S., Nikiforov, B. and B.G. Armstrong, 2003: Mortality and temperature in Sofia and London. *J. Epidemiol. Comm. Health*, **57**, 628-633.

Pope, C.A. III and L.S. Kalkstein, 1996: Synoptic weather modelling and estimates of the exposure-response relationship between daily mortality and particulate air pollution. *Environ. Health Perspect.*, **104**, 414-420.

Rainham, D.G. and K.E. Tomic, 2003: The Role of air pollution in the relationship between a heat stress index and human mortality in Toronto. *Environ. Res.*, **93**, 9-19.

Ramsey, T., Burnett, R.T., and D. Krewski, 2002: Underestimation of standard errors in generalized additive models linking mortality to ambient particulate matter. *Epidemiology*, **14**, 18-23.

Sheridan, S.C., 2002: The redevelopment of a weather-type classification scheme for North America. *Int. J. Clim.*, **22**, 51-68.

Smoyer, K.E., Kalkstein, L.S., Green, J.S. and H. Ye, 2000: The impacts of weather and air pollution on human mortality in Birmingham, Alabama and Philadelphia, Pennsylvania, *Int. J. Clim.*, **20**, 881-897.

Smoyer-Tomic, K.E., Kuhn, R. and A. Hudson, 2003: Heat wave hazards: an overview of heat wave impacts in Canada. *Natural Hazards*, **28**, 463-485.

Styer, P., McMillan, N., Gao, F., Davis, J., and J. Sacks, 1995: Effect of outdoor airborne particulate matter on daily death counts. *Env. Health Perspect.*, **103**, 490-497.

Wyzga, R.E. and F.W. Lipfert, 1994: Ozone and daily mortality: the ramifications of uncertainties and interactions and some initial regression results. AWMA Publication, VIP 54. AWMA Conference on Tropospheric Ozone, Orlando.

7. ACKNOWLEDGEMENTS

This study was funded by the Adaptation and Impacts Research Group of Environment Canada and the Natural Sciences and Engineering Research Council (NSERC) of Canada. The authors also wish to acknowledge the support of the McLaughlin Centre for Population Health Risk Assessment in the Institute of Population Health at the University of Ottawa.