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Synoptic weather typing applied to air pollution mortality among the elderly in 10 Canadian cities [☆]

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ABSTRACT

Background: Synoptic circulation patterns (large-scale weather systems) affect ambient levels of air pollution, as well as the relationship between air pollution and human health.

Objective: To investigate the air pollution–mortality relationship within weather types and seasons, and to determine which combination of atmospheric conditions may pose increased health threats in the elderly age categories.

Methods: The relative risk of mortality (RR) due to air pollution was examined using Poisson generalized linear models (GLMs) within specific weather types. Analysis was completed by weather type and age group (all ages, ≤ 64 , 65–74, 75–84, ≥ 85 years) in ten Canadian cities from 1981 to 1999.

Results: There was significant modification of RR by weather type and age. When examining the entire population, weather type was shown to have the greatest modifying effect on the risk of dying due to ozone (O₃). This effect was highest on average for the dry tropical (DT) weather type, with the all-age RR of mortality at a population weighted mean (PWM) found to be 1.055 (95% CI 1.026–1.085). All-weather type risk estimates increased with age due to exposure to carbon monoxide (CO), nitrogen dioxide (NO₂), and sulphur dioxide (SO₂). On average, RR increased by 2.6, 3.8 and 1.5% for the respective pollutants between the ≤ 64 and ≥ 85 age categories. Conversely, mean ozone estimates remained relatively consistent with age. Elevated levels of air pollution were found to be detrimental to the health of elderly individuals for all weather types. However, the entire population was negatively effected by air pollution on the hot dry (DT) and hot humid (MT) days.

Conclusions: We identified a significant modification of RR for mortality due to air pollution by age, which is enhanced under specific weather types. Efforts should be targeted at minimizing pollutant exposure to the elderly and/or all age groups with respect to weather type in question.

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1. Introduction

Complex relationships exist between meteorology, air pollution, and associated human health outcomes. Review of numerous

epidemiological time-series studies have shown that increased exposure to ambient air pollutants is a significant determinant of the number of daily deaths observed in an urban population (Anderson and Bell, 2009; Bell et al., 2005; Rainham et al., 2005; Smoyer et al., 2000). Exposure to weather elements is also a determinant of daily mortality that can co-vary with exposure to air pollution, and thus modify estimates of mortality risk. Hence, health risk models for air pollution often include weather-related variables as controls, such as air temperature (Anderson et al., 2001; Cakmak et al., 2006; Zanobetti and Schwartz, 2006).

The same has been observed in health risk models for overall weather effects, with common air pollutants such as ozone (O₃), nitrogen dioxide (NO₂), and sulphur dioxide (SO₂) often included as controls (Basu et al., 2005; Hajat and Haines, 2002a; Hajat et al., 2006; Medina-Ramon and Schwartz, 2007). Within urban areas,

Abbreviations: CO, carbon monoxide; AIC, Akaike's Information Criteria; DM, dry moderate; DP, dry polar; DT, dry tropical; GLM, generalized linear model; MM, moist moderate; MP, moist polar; MT, moist tropical; NO₂, nitrogen dioxide; O₃, ozone; PM, particulate matter; PWM, population weighted mean; SO₂, sulphur dioxide; TR, transitional; RR, relative mortality risk

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Table 1
National Ambient Air Quality Standards (NAAQS), physical sources, chemical pathways of formation, and health effects of the air pollutants in the current study.

Pollutant	Acceptable Level ^a	Main Sources in Canada ^c	Main chemical pathways of formation ^{e,f}	Health effects
O ₃	15 ppb	Secondary pollutant	[1a] NO ₂ +hv→NO+O [1b] NO ₂ +O ₂ +hv→O ₃ +NO [1c] O+O ₂ →O ₃ [1d] CO+2O ₂ +hv→CO ₂ +O ₃ [2a] O ₃ +NO→NO ₂ +O ₂	Reduces lung function, inflames lungs, scar lung tissue ^c . Chest pain, coughing, throat irritation, congestion; worsens bronchitis, asthma and emphysema ^d
NO ₂	32 ppb ^b	Lightning, forest fires, high temperature combustion car engines, power plants, industrial processes	[2b] HO ₂ +NO→OH+NO ₂ [2c] OH+NO ₂ →HNO ₃	Lung irritation, decrease lung function, increase susceptibility to allergens for asthmatics ^c
CO	5 ppm	Vehicle emissions, coal combustion	Emitted primarily as raw material	Headache, nausea, weakness, potential long-term health effects ^d
SO ₂	57 ppb	Fuel combustion for electricity and heating, coal burning, metal smelting/refining, pulp and paper, flaring of wells	Emitted primarily as raw material	Adverse effects on respiratory systems of humans due to irritation and airway obstruction ^c

^a Mean daily acceptable level, NAAQS objectives and guidelines health Canada, 2006.

^b Annual value; daily not available.

^c Environment Canada (2013).

^d U.S.EPA (2010).

^e Notario et al.2012.

^f Finlayson-Pitts and Pitts (2000).

atmospheric chemistry is complex, and is modulated by humidity, temperature, short- and long-wave radiation, and other factors, which in combination affect the degree of human exposure to harmful air pollutants (Portier et al., 2010). According to Basu (2009), the daily associations of ambient air temperature and pollution make it critical to separate the independent effects of each.

Triggers for adverse health effects of air pollution, particularly respiratory impacts, vary among urban areas and are based on climatic factors, vehicle emissions, and characteristics of the built environment (Portier et al., 2010). The most recent report of the International Panel on Climate Change (IPCC) (Parry et al., 2007) stated that within 20 years, 81% of the population in more-developed regions will be living in urban areas, which is where atmospheric problems are most frequent, largely due to traffic emissions (Notario et al., 2012). Emissions from vehicles and other industrial sources consist of the primary air pollutants carbon monoxide (CO), SO₂, NO₂, nitrogen oxide (NO), and particulate matter (PM), which give rise to secondary pollutants such as O₃ (Finlayson-Pitts and Pitts, 2000) (Table 1). NO and NO₂ (NO_x) are at the centre of urban atmospheric photochemistry (as shown in Eqs. (1a), (1b) and (2a)–(2c) in Table 1). The reaction of NO with O₃ (Eq. (2a)) controls the development of ozone peaks in urban areas (Finlayson-Pitts and Pitts, 2000; He and Lu, 2012). Ozone levels increase significantly due to strong solar radiation and high temperature (see Eqs. (1a)–(1c)) (He and Lu, 2012), thus it has a close relationship with both meteorological variables and NO_x.

Previous time-series models designed specifically to estimate air pollution and/or weather effects may underestimate the net mortality effect because they do not consider the air pollution-weather interactions and/or modifying effects. Results of such studies also do not always point to significant interactions of weather and air pollution. In a study of daily mortality in nine California counties by Basu et al. (2008), no air pollutant (O₃, CO, NO₂, and PM) was found to modify the temperature effect on mortality. Samet et al. (1998) found that adjusting for synoptic weather categories did not change the association between mortality and air pollution indices in Philadelphia, USA. Conversely, in a study in Toronto, Canada, Rainham et al. (2005) found that by controlling for synoptic weather in the troposphere, air

pollution had a small but consistent modifying effect on daily relative mortality risk.

However, such inconsistencies regarding the differential impacts of weather and air pollution on mortality may be partly explained by the simplistic way in which we treat weather (i.e., single variables), which can underestimate the impact of meteorological extremes (Smoyer et al., 2000). A synoptic method (air mass-based approach) works on the underlying assumption that the impacts of various weather variables are ‘holistic’ in nature and should be used in combination (Smoyer et al., 2000). Spatial synoptic classification (SSC) (Sheridan, 2002) has been used to study human health outcomes, age-related effects, and air pollution variations under the various synoptic weather types (e.g., Greene et al., 1999; Hanna et al., 2011; Rainham et al., 2005). Further, air pollution and weather studies have also identified the elderly as a vulnerable population (Anderson and Bell, 2009; Basu, 2009; Diaz et al., 2002a,b; Portier et al., 2010). Individuals ≥ 85 years of age have been found to be more than twice as likely to die from high levels of PM₁₀, and 50% more likely to die due to increases in levels of O₃ and SO₂ (Cakmak et al., 2007). Heat effects were found by Anderson and Bell (2009) to be greatest for those ≥ 75 years of age.

We investigated the above issues and impacts on human health by examining the air pollution–mortality relationship within weather types and seasons, assessing mortality in five age categories. We applied a Poisson GLM to empirical air pollution measurements (O₃, NO₂, CO, SO₂) and synoptic scale categories, with data collected between 1981 and 1999 inclusive for ten Canadian cities. From this, we examined if specific pollutants resulted in a higher risk for the elderly, and how season and weather type affect this relationship.

2. Materials and methods

2.1. Data sources

We combined 19 years of daily mortality and air pollution data (1981–1999) for ten Canadian cities: Calgary, Edmonton, Montreal, Ottawa, Quebec City, St. John, Toronto, Vancouver, Windsor, and Winnipeg. We accessed daily mortality data from the Canadian Institute for Health Information (CIHI) database for 1981 to 1999 inclusive, including all non-accidental (ICD9 < 800) deaths, stratified by age group:

≤ 64, 65–74, 75–84 years, and ≥ 85, and all ages together. National Air Pollution Surveillance (NAPS) Network air pollution data were provided by Environment Canada. These data consisted of mean daily ambient concentrations of carbon monoxide (CO, ppm), nitrogen dioxide (NO₂, ppb), sulphur dioxide (SO₂, ppb) and ground-level ozone (O₃, ppb). Hourly weather data from city airports were downloaded from the National Climate Data and Information Archive.

2.2. Classification of synoptic weather types

Information of daily synoptic weather types (commonly referred to as air masses), was accessed from the spatial synoptic classification (SSC) website (<http://sheridan.geog.kent.edu/ssc.html>). The SSC system is a semi-automated statistical approach designed to group complex daily weather conditions under one of several distinct categories or classifications (Sheridan, 2002). The extraction of daily synoptic weather types for the SSC is based on measurements of air temperature, dew point temperature, sea level pressure, cloud cover, and wind velocity at four equally spaced times throughout the day (0300, 0900, 1500, 2100 h). Sliding seed days are used to represent expected and observed meteorological conditions at each location throughout the year for each weather type. Each seed day was quantified by typical meteorological variables for the location and time of year, with ranges specified to indicate threshold values for each weather type. This procedure allows for spatial and temporal relativity, where the characteristics of select weather types would differ throughout the year (Supplementary Table 1). The weather types include: dry moderate (DM), dry polar (DP), dry tropical (DT), moist moderate (MM), moist polar (MP) and moist tropical (MT), plus a transitional (TR) category representing a shift from one weather type to another. A description of each weather type can be found in Sheridan (2002) and Rainham et al. (2005).

2.3. Data analysis

A cross-sectional analysis of the weather type, air pollution, and mortality was completed, giving descriptive statistics of means and standard deviations for each weather type in all 10 cities. Paired *t*-tests were employed to determine if a weather type result differed significantly from the mean for all weather types. This was also done to compare the city-specific results to the mean for all cities, using a level of statistical significance of $p < 0.05$. Time-series analysis of daily mortality, air pollution, and weather type was carried out by fitting a piece-wise Poisson GLM to the residuals, thereby estimating risk of mortality associated with exposure to air pollution within each weather type. A smooth curve was fit to the time-series data using a natural spline to control for other potential factors with time (i.e., smoking, influenza).

Statistical analysis was performed as described in Cakmak et al. (2006). Each time-series model for each city included indicator variables for the day-of-week, and was adjusted for temporal trends using natural spline functions for day of study, with a knot for each of 30, 90, 180, 270, and 365 days of observation. The optimal model was selected based on the number of knots that either minimized the Akaike's Information Criteria (AIC) – a measure of model prediction – or maximized the evidence that the model residuals did not display any type of structure. The latter included serial correlation in the residuals and was completed using Bartlett's test. Finally, each air pollutant was added to the model containing natural splines and indicator variables. Once the final model was selected, the confidence intervals for RR were generated across each weather type for each city.

The air pollution-effect estimate for the *j*th city, $\hat{\beta}_j$, was assumed to be normally distributed with β and variance $\Theta + \hat{v}_j$, where \hat{v}_j is the estimation variance of $\hat{\beta}_j$ and Θ is the variance of the true air pollution effect between cities. The estimate of the pooled air pollution effect among cities is given by:

$$\hat{\beta} = (\sum(\hat{\Theta} + \hat{v}_j)^{-1})^{-1} \times \sum(\hat{\Theta} + \hat{v}_j)^{-1} \hat{\beta}_j \quad (3)$$

where $\hat{\Theta}$ is the maximum likelihood estimate of Θ . The estimate of the standard error of $\hat{\beta}$ is given by:

$$(\sum(\hat{\Theta} + \hat{v}_j)^{-1})^{-1/2} \quad (4)$$

In the second stage of analysis, a pooled estimate across all 10 cities was calculated using a random-effects model that weights the effect estimates by the inverse sum of within- and between-city variance, thus accounting for any heterogeneity among the cities in the pooled-effect estimates. We reported percent change in daily mortality associated with a change equivalent to population weighted mean (PWM) level of air pollutants, and their 95 percent confidence intervals (CI). *Q*-statistics were used to assess statistical heterogeneity in effect size between cities. Significance testing for models was completed using *t*-tests, with a *p*-value of < 0.001 indicating statistical significance. All statistical analyses were completed using R 2.10.1 (The R foundation for Statistical Computing 2008).

3. Results

3.1. Frequency and meteorology of weather types

Weather type characteristics varied across the country (Supplementary Table 1). Overall, DM and DP weather type days were the most frequent, excluding the coastal cities of St. John's and Vancouver, where the moist conditions of MM and MP were the most prevalent. Moist tropical weather (MT) in general was infrequent in the two coastal cities year-round (maximum seasonal frequency of 9.0%), and rare in the winter and fall seasons. The combined most humid and hot air of MT had the highest frequency in the summer season for the mid-eastern cities (18.6% average). A second harmful weather type, dry tropical (DT), is the hottest and driest, yet it is rare throughout Canada in the summer and non-existent in the winter. It was present an average of 3.5 summer days per year in the central cities (maximum seasonal frequency of 4.8%), thus giving fewer days to examine.

3.2. Air pollution and mortality by weather type and city

Study-period mean levels of air pollution (Table 2) varied by city, with no systematic annual patterns yet differed by weather type. Seasonal air pollution concentrations in each city also varied by weather type (Supplementary Table 2). The DT weather type had significantly higher concentrations of NO₂ and O₃ when compared to the all-weather type mean (Table 3). Additionally, the MT weather type had significantly higher NO₂ and O₃ concentrations in the summertime, while full-year analysis showed greater overall O₃ concentrations. On average for all ten cities, the DT weather type was found to have the highest yearly average concentrations of O₃ (30.3 ppb), NO₂ (25.0 ppb), and SO₂ (6.0 ppb).

Conversely, significantly lower concentrations of CO were found under the MP weather type (winter, spring, summer), NO₂ (all seasons), and O₃ (spring, summer, fall), with DP and MM weather associated with significantly lower O₃ concentrations. TR similarly had many significantly lower concentrations of pollutants year-

Table 2

Mean and standard deviations for air pollution, weather, population and mortality data for all cities, 1981 to 1999.

	Calgary	Edmonton	Montreal	Ottawa	Quebec City	St. John's	Toronto	Vancouver	Windsor	Winnipeg
Population ^a	721,137	606,580	1796,020	672,490	491,211	251,258	2333,466	1617,711	274,418	612,633
Daily mortality	9.4 ± 3.4	10.5 ± 3.5	46.8 ± 8.9	14.6 ± 4.5	16.4 ± 4.7	2.9 ± 1.7	45.8 ± 7.8	28.1 ± 6.7	5.7 ± 2.5	13.8 ± 4.0
CO (ppm)	1.1 ± 0.7	1.2 ± 0.8	0.8 ± 0.6	0.9 ± 0.5	0.7 ± 0.6	0.7 ± 0.6	1.3 ± 0.6	1.1 ± 0.7	0.8 ± 0.5	0.6 ± 0.3
NO ₂ (ppb)	26.4 ± 9.2	25.8 ± 10.5	22.4 ± 8.5	19.3 ± 8.7	20.6 ± 11	10 ± 8.3	25.7 ± 8.3	21.0 ± 6.8	26.0 ± 10.0	14.6 ± 7.3
SO ₂ (ppb)	3.3 ± 2.6	2.3 ± 2.0	6.6 ± 6.0	4.5 ± 4.3	7.0 ± 13.3	8.5 ± 9.1	4.8 ± 4.2	4.9 ± 3.0	7.9 ± 4.9	0.9 ± 1.4
O ₃ (ppb)	17.6 ± 8.5	16.7 ± 9.1	14.5 ± 8.8	16.0 ± 8.7	16.2 ± 9.1	23.2 ± 9.7	17.3 ± 9.7	12.8 ± 6.7	18.8 ± 12.4	17.9 ± 8.7
Temperature (°C)	4.7 ± 11.3	2.8 ± 12.5	6.6 ± 12.1	6.2 ± 12.3	4.5 ± 12.2	5.3 ± 10.3	7.8 ± 10.8	10.3 ± 6.1	9.2 ± 10.7	3.0 ± 14.5
Dew-point (°C)	-3.2 ± 9.6	-2.8 ± 11.2	1.2 ± 11.8	0.5 ± 11.9	-0.8 ± 12.1	1.0 ± 10.9	2.8 ± 9.8	6.8 ± 5.5	3.8 ± 10.0	-2.1 ± 13.2
Wind speed (m/s)	4.0 ± 2.8	3.4 ± 2.3	3.8 ± 2.4	3.5 ± 2.3	3.7 ± 2.7	4.1 ± 2.8	4.0 ± 2.6	3.2 ± 2.3	4.3 ± 2.6	4.7 ± 2.7

^a Average population for 19 year study period, Statistics Canada.

Table 3
Average ten city mean values and standard deviations of air pollution levels and all-cause mortality by weather type and season (1981–1999).

Pollutant	Season	Dry moderate Mean ± SD	Dry polar Mean ± SD	Dry tropical Mean ± SD	Moist moderate Mean ± SD	Moist polar Mean ± SD	Moist tropical Mean ± SD	Transition Mean ± SD	Mean all weather types Mean ± SD
CO (ppm)	All	0.9 ± 0.26	1.0 ± 0.29	1.0 ± 0.31	1.0 ± 0.27	0.9 ± 0.24	1.0 ± 0.35	0.8 [^] ± 0.23	0.94 ± 0.08
	Winter	1.2 ± 0.33	1.1 ± 0.40	- ± -	1.2 ± 0.33	1.0 [^] ± 0.29	1.3 ± 0.46	1.0 [^] ± 0.28	1.13 ± 0.12
	Spring	0.8 ± 0.22	0.7 ± 0.22	0.9[*] ± 0.32	0.8 ± 0.25	0.7 [^] ± 0.20	0.8 ± 0.25	0.7 [^] ± 0.20	0.77 ± 0.08
	Summer	0.8 ± 0.22	0.7 ± 0.23	0.9 ± 0.46	0.8 ± 0.25	0.7 [^] ± 0.22	0.9[*] ± 0.23	0.7 [^] ± 0.19	0.79 ± 0.09
	Fall	1.1 ± 0.37	1.1 ± 0.42	1.0 ± 0.39	1.1 ± 0.33	1.0 ± 0.29	1.3 ± 0.73	0.9 [^] ± 0.31	1.07 ± 0.13
NO ₂ (ppb)	All	22.1 ± 5.78	21.8 ± 5.76	25.0[*] ± 6.02	21.1 ± 5.56	19.8 [^] ± 5.25	22.0 ± 6.42	19.5 [^] ± 5.12	21.05 ± 1.14
	Winter	27.6 ± 6.69	25.9 ± 7.63	- ± -	25.7 ± 7.23	24.0 [^] ± 6.20	27.4 ± 9.94	23.0 [^] ± 6.71	25.60 ± 1.83
	Spring	21.3 ± 5.24	18.5 [^] ± 4.76	26.7[*] ± 6.51	20.2 ± 5.37	17.7 [^] ± 4.90	22.0 ± 6.00	18.1 [^] ± 4.34	19.63 ± 1.79
	Summer	19.7 ± 5.25	16.5 [^] ± 4.56	23.2[*] ± 9.52	17.5 ± 4.53	15.1 [^] ± 4.00	21.4[*] ± 5.62	16.3 [^] ± 4.34	17.75 ± 2.36
	Fall	23.4 ± 6.89	22.6 ± 7.11	26.6[*] ± 4.86	21.4 ± 6.38	20.1 [^] ± 5.54	23.0 ± 8.68	19.7 [^] ± 6.11	21.70 ± 1.55
SO ₂ (ppb)	All	5.4 ± 2.86	5.2 ± 2.29	6.0[*] ± 3.68	5.0 ± 2.79	5.0 ± 2.69	5.0 ± 2.83	4.8 [^] ± 2.28	5.07 ± 0.21
	Winter	7.2 ± 3.62	6.6 ± 3.01	- ± -	6.3 ± 3.44	6.2 ± 3.50	7.0 ± 3.93	6.3 ± 3.06	6.60 ± 0.41
	Spring	5.4[*] ± 3.82	4.2 [^] ± 2.63	6.9 ± 5.74	4.6 ± 3.40	4.0 ± 3.09	5.3 ± 3.12	4.3 ± 2.52	4.96 ± 1.01
	Summer	4.5[*] ± 2.68	3.4 [^] ± 1.78	4.2 ± 3.03	4.2 ± 3.04	3.3 ± 1.85	4.8 ± 3.52	3.4 [^] ± 1.83	3.97 ± 0.60
	Fall	5.9[*] ± 2.62	5.1 ± 2.29	5.9 ± 4.03	5.2 ± 2.31	4.8 [^] ± 2.39	6.6 ± 2.81	4.7 [^] ± 2.14	5.46 ± 0.69
O ₃ (ppb)	All	19.0 ± 2.39	15.6 [^] ± 2.98	30.3[*] ± 5.03	15.3 [^] ± 3.29	13.8 [^] ± 4.08	23.0[*] ± 4.76	17.8 ± 2.70	19.26 ± 5.73
	Winter	15.8 ± 3.35	14.9 ± 3.98	- ± -	12.9 ± 4.17	14.7 ± 4.15	12.7 [^] ± 4.57	16.4[*] ± 3.28	14.57 ± 1.50
	Spring	25.3 ± 3.20	22.7 [^] ± 2.50	35.0[*] ± 7.40	21.0 [^] ± 3.48	19.7 [^] ± 3.62	26.0 ± 3.60	24.7 ± 2.97	24.91 ± 5.01
	Summer	20.0 ± 4.09	14.5 [^] ± 2.97	28.4[*] ± 8.75	17.9 [^] ± 3.96	12.8 [^] ± 4.40	27.0[*] ± 3.55	18.7 [^] ± 3.02	19.90 ± 5.88
	Fall	11.3 ± 2.77	11.3 ± 3.89	16.7[*] ± 5.38	9.1 [^] ± 4.41	9.3 [^] ± 3.56	12.4 ± 6.00	13.0[*] ± 3.47	11.87 ± 2.58
Mortality non-accidental	All	18.9 ± 15.29	19.5 ± 15.85	18.3 ± 16.18	19.3 ± 15.57	19.7 ± 16.23	19.2 ± 15.40	19.8 ± 16.27	19.24 ± 0.52
	Winter	20.8 ± 17.14	21.0 ± 17.12	- ± -	21.0 ± 17.08	21.3 ± 17.70	20.9 ± 17.35	21.6 ± 17.84	21.10 ± 0.30
	Spring	18.7 ± 15.29	18.6 ± 15.00	18.2 ± 16.23	18.8 ± 15.20	18.7 ± 15.07	19.3 ± 15.50	18.9 ± 15.57	18.74 ± 0.33
	Summer	17.9 ± 14.48	17.5 [^] ± 14.01	18.2 ± 16.74	17.9 ± 14.32	17.4 [^] ± 14.00	19.3 ± 15.09	18.0 ± 14.68	18.03 ± 0.63
	Fall	19.6 ± 15.75	19.6 ± 15.78	20.9 ± 16.17	20.0 ± 16.02	19.8 ± 15.95	20.6 ± 17.17	20.1 ± 16.20	20.09 ± 0.50

* Indicates values being significantly greater than the all-weather type mean for given variable, as shown in the far right column of mean values, for all air pollutants and non-accidental mortality each season ($p < 0.05$).

[^] Indicates values as significantly lower.

round. Significantly lower mortality occurred within the summertime DP and MP weather types, with no weather type demonstrating significant increases in mortality.

3.3. Relative mortality risks

3.3.1. All-age relative risk of mortality

When examining all-age combined effects, weather type was shown to have significant modifying effects on the risk of dying due to O₃ exposure, yet weather types did not significantly modify the RR due to CO, NO₂, or SO₂ (Fig. 1; Table 4). The increase in RR due to O₃ was significantly increased in the DT and MT weather types, with MT posing the most significant risk, e.g., RR = 1.038 (95% CI 1.021–1.055) for summer and 1.062 (95% CI 1.032–1.093) for spring. During the spring and summer seasons, the air pollution–mortality associations varied more with weather type, with less variation in the fall and winter.

All seasons displayed a significant increase in the risk of dying due to O₃ exposure, with the highest RR estimate for the full population found in the winter (RR = 1.054 (95% CI 1.030–1.078)). The all-age effects of air pollution was overall the most harmful to human health during DT weather, with risk of mortality increasing by 5.5% for O₃ and 5.1% for NO₂ (Table 4). This risk of dry air in the summertime (DM, DP, DT) posed a significantly greater overall risk due to all pollutants for all ages when compared to such weather in the fall and spring seasons. For example, from Fig. 1, we see the NO₂ and SO₂ estimates to be significantly greater in the dry versus the moist weather types (MM, MP, MT).

3.3.2. Relative risk by age

Fig. 2 illustrates that the susceptibility to the air pollutants NO₂, CO, and SO₂ increased relatively proportionately with age in all weather types and seasons. However, O₃ effects remained

consistent with increasing age, or became insignificant (Supplementary Table 3); hence, the RR due to O₃ was not modified by age. The risk of individuals ≥ 85 years of age dying due to CO, NO₂, and SO₂ was significantly modified by weather type (Fig. 3), with all weather types (excluding DT and MT) found to have significant increases in the risk of mortality. No weather type was found to significantly increase the risk of dying due to O₃ for individuals ≥ 85 years of age. The highest risks of mortality in the ≥ 85 years for full year analysis (Fig. 4; Supplementary Table 3), were due to exposure to NO₂ in DM air (i.e., 1.080 (95% CI 1.066–1.095)) and DP air (i.e., 1.082 (95% CI 1.068–1.095)).

The largest mortality effect sizes were consistently found in the DT weather type due to O₃ exposure in all individual age categories (excluding ≥ 85) (e.g., RR = 1.059 (95% CI 1.011–1.122) for ≤ 64, 1.083 (95% CI 1.029–1.136) for 65–74, and 1.081 (95% CI 1.029–1.136) for 75–84 years of age). This mortality risk in DT was also significantly higher than for all other weather types (with the exclusion of MT for those ≤ 64 years of age).

However, the modifying effects of age on the air pollution–mortality relationship were significantly different within each season when compared by weather type. When examining the weather type and age group (≤ 64 versus ≥ 85 years) modifying effects together, as displayed in Fig. 3, the modifications present did not show a pattern due to a specific weather type or pollutant. On average, RR increased by 2.6, 3.8 and 1.5% for the respective pollutants between the ≤ 64 and ≥ 85 age categories, as displayed in Fig. 2. The highest numbers of significant differences due to age were found in the spring season. For example, significantly higher risk estimates were present in the springtime MT weather type for individuals ≥ 85 years of age due to O₃ and NO₂ exposure.

Carbon monoxide displayed the largest number of significant effects for this age comparison. The harm of CO exposure is exemplified in the DM weather type, where the risk estimates

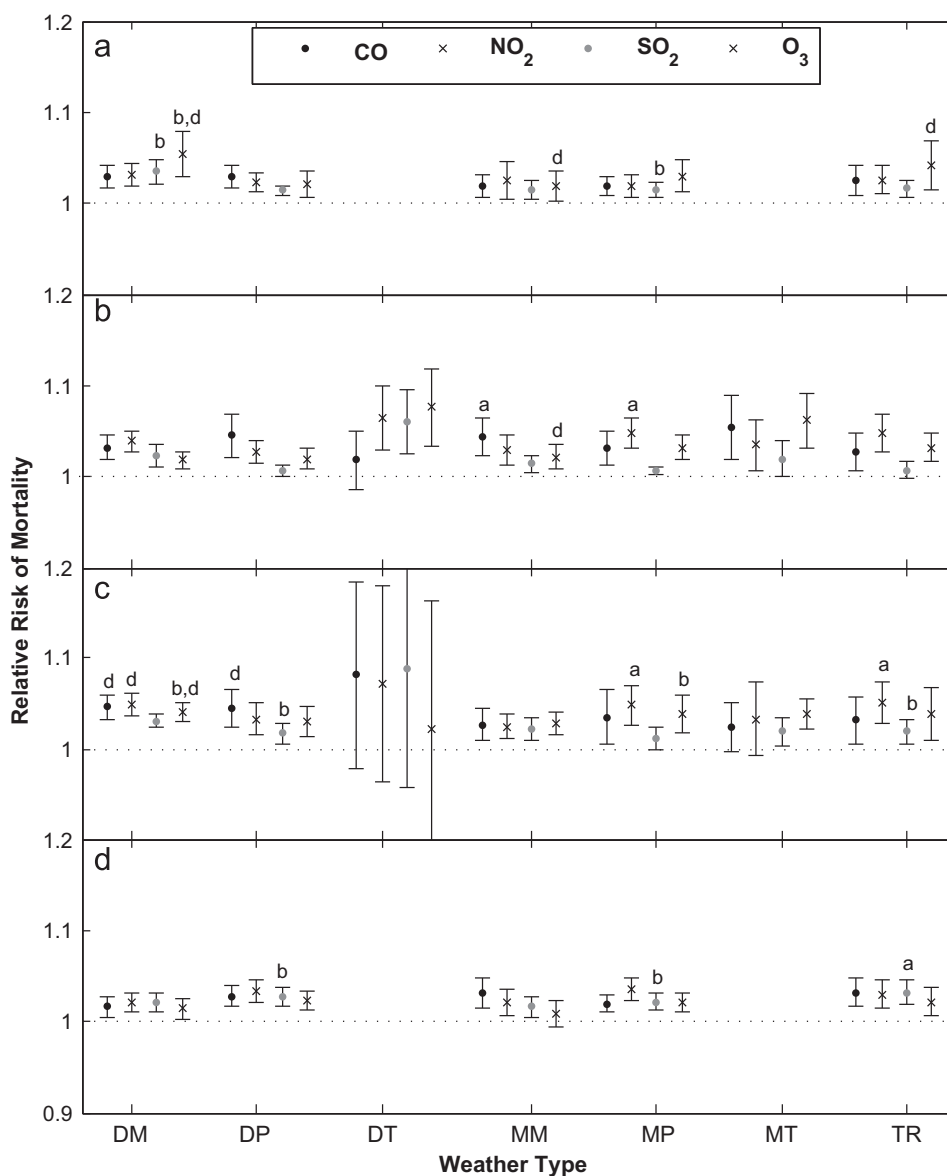


Fig. 1. All-age pooled relative risks of mortality due to air pollution by season and weather type ((a) Winter; (b) Spring; (c) Summer; (d) Fall), with 95% confidence intervals (CI). Letters indicate the given season (plot) to be significantly greater ($p < 0.05$) than the corresponding lettered plot as denoted above the data point. For example, in plot a: Winter, the letter 'b' above an RR estimate denotes that the given estimate in the winter (plot a) is significantly greater than in the spring (plot b). Wide CI values extending off the graph can be seen Supplementary Table 3.

Table 4

Relative mortality risk (RR) estimates pooled across ten cities for all ages, with lower and upper 95% confidence intervals (CI) and for four pollutants within synoptic weather type (1981–1999).

Mortality category	Weather type	CO (ppm)		NO ₂ (ppb)		SO ₂ (ppb)		O ₃ (ppb)	
		RR	(CI)	RR	(CI)	RR	(CI)	RR	(CI)
Non-accidental									
All ages									
	DM	1.033*	(1.028, 1.038)	1.047*	(1.041, 1.052)	1.025*	(1.016, 1.034)	1.026*	(1.019, 1.033)
	DP	1.042*	(1.033, 1.051)	1.047*	(1.039, 1.056)	1.027*	(1.021, 1.034)	1.017*	(1.009, 1.025)
	DT	1.030*	(1.006, 1.054)	1.051*	(1.026, 1.077)	1.035*	(1.012, 1.058)	1.055*	(1.026, 1.085)
	MM	1.038*	(1.029, 1.047)	1.041*	(1.031, 1.051)	1.026*	(1.015, 1.037)	1.020*	(1.011, 1.029)
	MP	1.032*	(1.023, 1.041)	1.048*	(1.042, 1.054)	1.025*	(1.015, 1.034)	1.025*	(1.012, 1.038)
	MT	1.029*	(1.014, 1.045)	1.028*	(1.017, 1.039)	1.017*	(1.008, 1.027)	1.039*	(1.019, 1.060)
	TR	1.031*	(1.023, 1.039)	1.041*	(1.033, 1.049)	1.027*	(1.021, 1.033)	1.018*	(1.005, 1.030)
Mean ± SD^a		1.034 ± 0.005		1.043 ± 0.008		1.026 ± 0.005		1.029 ± 0.014	

are significantly higher in the spring, summer, and fall. Further, MM air resulted in significantly higher risks of dying from air pollution at ≥ 85 years of age in all seasons but winter. These

results for the MM and DM weather types highlight an important observation, whereby risk estimates are frequently found to be statistically higher in the moderate ('fair-weather') air masses.

Due to low numbers of DT observations in Canada, the findings for this weather type may be weaker and more difficult to draw conclusions from, and result in wide confidence intervals (Figs. 1 and 3); thus, such results should be considered with caution.

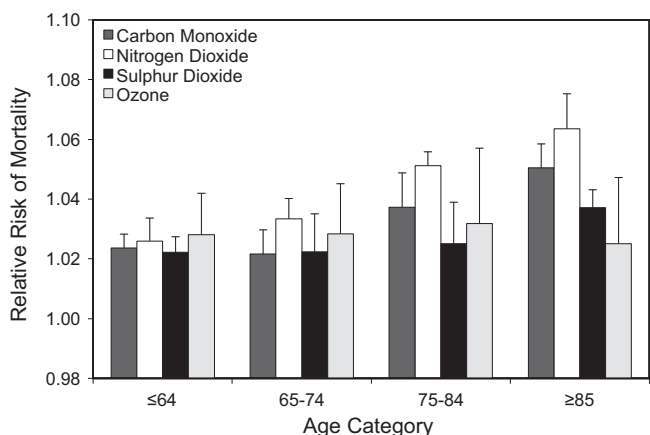


Fig. 2. Mean pooled relative mortality risks with standard deviation of four age categories, from left to right as follows: ≤ 64 years; 65–74 years; 75–84 years; and ≥ 85 years. Results are for full-year analysis and presented separately for four air pollutants: carbon monoxide (dark grey), nitrogen dioxide (white), sulphur dioxide (black) and ozone (light grey).

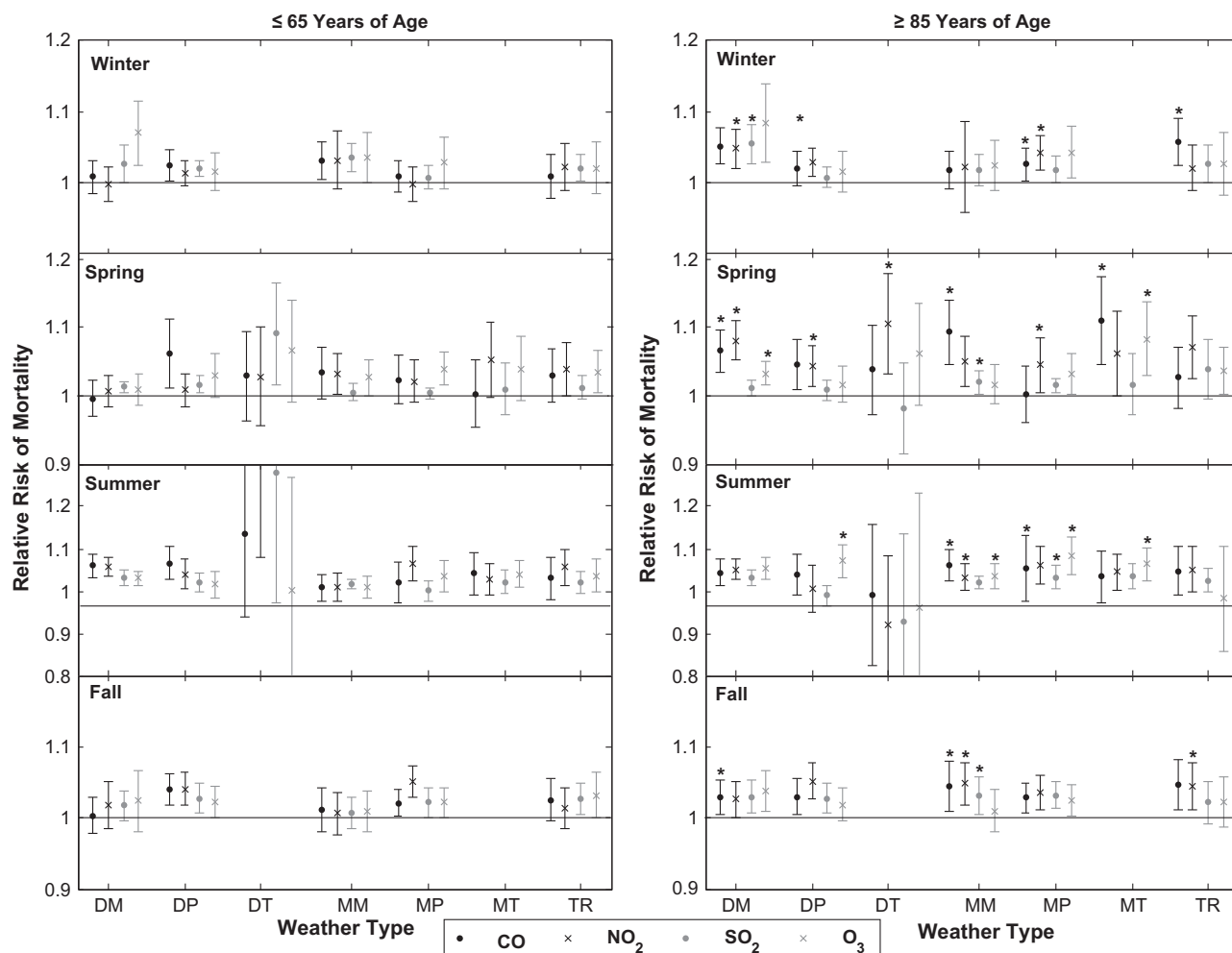


Fig. 3. Pooled relative risks of mortality due to air pollution by season and weather type, with 95% confidence intervals (CI). Data on four air pollutants (CO, NO₂, SO₂, O₃) are displayed per weather type, and grouped under age categories: (1) ≤ 64 years (left); (2) ≥ 85 years (right). Asterisk indicates the given RR estimate in the ≥ 85 age group to be significantly greater than the RR value for the ≤ 64 age category ($p < 0.05$). Wide CI values extending off the graph can be seen Supplementary Table 3.

4. Discussion

4.1. Air pollution within weather types

The ten cities were shown to have different results in terms of average air pollution concentrations, which is due to the differing types of climates, topographical controlling effects, and sources of air pollution. Vancouver and other coastal cities, being commonly cloudy and moderate, were at lower risk of ozone formation due to a lack of heat and sunlight that promote photochemical reactions to proceed (e.g., Table 1). However, these conditions were common in many mid-eastern cities (e.g., Toronto, Montreal, Ottawa, Windsor, Winnipeg). Variable levels of air pollution within weather type are commonly found within large countries, as found by Greene et al. (1999) in four cities across the United States, with the highest concentrations commonly found in the hot oppressive weather categories. The weather type averages for all cities (Supplementary Table 2) highlight how the outdoor air pollution concentration is associated with specific weather types, agreeing with similar studies using the synoptic weather typing (Davis et al., 2010; Greene et al., 1999; Hanna et al., 2011; Cheng and Lam, 2000; Rainham et al., 2005; Smoyer et al., 2000).

The relatively lower air pollution levels found in the coldest weather type, DP, for the winter season agree with SSC studies completed by Rainham et al. (2005) in Toronto, Canada, and by Kalkstein and Sheridan (2011) in Korean cities. High O₃

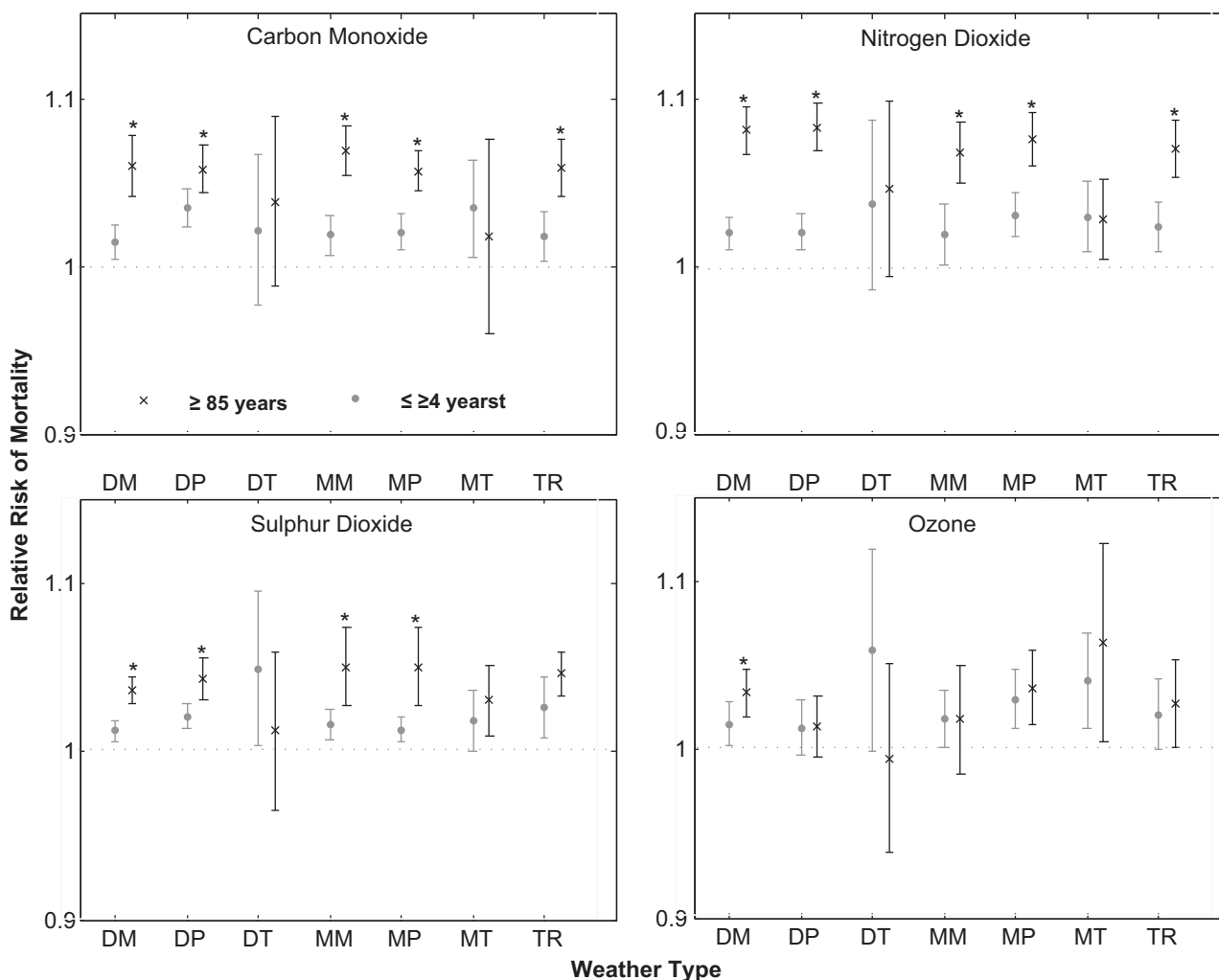


Fig. 4. Pooled relative risks of mortality due to air pollution for two age groups: (1) ≤ 64 years; (2) ≥ 85 years, examined by air pollutant and for each weather type. Pollutants include: (a) carbon monoxide; (b) nitrogen dioxide; (c) sulphur dioxide; and (d) ozone. Asterisk indicates the given RR estimate as being significantly greater than the RR value for the ≤ 64 age category ($p < 0.05$).

concentrations in hot–warm and dry conditions (DM and DT), as well as hot moist conditions (MT), were also found by Davis et al. (2010) and Hanna et al. (2011) in the warm season. Further, elevated spring and summer ozone levels were found by Hanna et al. (2011) to be associated with DM, DT, and MT weather types, with the highest in DT, which align with the current study results.

Clear skies, high pressure, and abundant sunlight that are associated with the DT weather type result in photochemical reactions, which lead to the formation of the secondary pollutant O_3 and ‘trapping’ of many air pollutants (Smoyer et al., 2000; Davis et al., 2010; Hanna et al., 2011) (Table 1). Although large diurnal variations are found in ground-level air pollutants (He and Lu, 2012), daily SSC analysis did not allow assessment of the large fluctuations of pollutants. For example, NO_2 and O_3 concentrations are commonly inversely related, as depicted by the equations in Table 1 (He and Lu, 2012; Notario et al., 2012).

4.2. Relative risks of mortality due to air pollution

Results demonstrate how the air pollution effects on human health differ with atmospheric conditions. Ambient air pollution has been shown numerous times to be altered by SSC weather type (Greene et al., 1999; Rainham et al., 2005; Kalkstein, 1995; Hanna et al., 2011), aggravating pre-existing respiratory conditions

and leading to other effects on human health (Portier et al., 2010). The synoptic circulation patterns (weather types) in the current study were found to affect the risk of mortality, as well as the modifying the effects of age on the specific air pollution–mortality relationship. This was shown to be most dependant on the age category and air pollutant being studied.

The interactions of the secondary pollutant O_3 with a full suite of atmospheric conditions (Davis et al., 2010; Hanna et al., 2011) resulted in the most variable air pollution–mortality associations when assessed by weather type, yet not with age. This may be due to elderly individuals over the age of 85 spending most of their time indoors, where concentrations of O_3 are extremely low due to this pollutant’s inability to infiltrate closed buildings, and thus levels are commonly found to be below detection levels (Heroux et al., 2010). The stark contrast in mortality risks at ≥ 85 years of age due to CO, NO_2 , and SO_2 was found in the moderate and cool weather types (DM, DP, MM, MP) in spring and summer; however, on extreme days of DT and MT, all age groups were shown to be at risk of dying. This may be due to the interaction of heat with high levels air pollution (Smoyer et al., 2000; Smoyer-Tomic et al., 2003). Hence, the health focus on MT and DT days shifts to all ages of the population, rather than just the elderly. Rainham et al. (2005) also found RR to increase for all ages with same-day O_3 exposure within the summer DT air, as well as due to NO_2 in the

DM weather type. We found this to be true for all summertime dry weather types at all ages, based on air pollution–mortality associations pertaining to NO₂ and SO₂.

This provides evidence for the potential use of graded targeted warnings that would alert the elderly of greater air pollution levels, based on the presence of low-to-high risk conditions, which can then inform behavioural actions (e.g., remaining indoors) and adaptation efforts. The further segregation of risk based on weather type allows for calling a high-risk warning exclusive to the elderly population on all weather-type days, yet the presence of hot dry or moist tropical weather would elicit a higher risk for the entire population.

Risks can be adapted by season, as slightly differing RR estimates were found by season. For example, summertime moist weather types of MM, MP, and MT air are crucial indicators of harmful air that is associated with higher mortality, particularly in the higher ages groups. Therefore, in addition to increased susceptibility of all age groups during hot, moist tropical weather, all summertime humid weather types pose a significant RR for those aged ≥ 85 .

With the age distribution in Canada skewing to the older-age groups, these results are of great importance to the health of Canadians, and also apply to many countries worldwide. It has been shown that using generalized air pollution thresholds is not indicative for a whole population (Cakmak et al., 2011), since many population subgroups are more susceptible to air pollution and weather effects than others. In addition to the vulnerable elderly considered here, additional groups include children, persons of low socio-economic status that are socially disadvantaged (Cakmak et al., 2011), people living near dense traffic roadways (Cakmak et al., 2012) and those with pre-existing respiratory or cardiac conditions (Portier et al., 2010). New research is needed to develop targeted mitigation and adaptation strategies that can positively affect human health; these would include reducing precursors to ozone and thus the associated health effects based on age vulnerability (Portier et al., 2010).

Rainham et al. (2005) demonstrated that moderate weather (DM, MM), rather than extreme days, show little mortality relationship with weather type, but potentially result in stronger mortality predictions when combined with air pollution. Similar results depicting harmful health effects in moderate weather were cited by Hanna et al. (2011), Samet et al. (1998), and Smoyer et al. (2000), and were also found in the current study in the age-based seasonal analysis. In the case of DM and MM, the association of air pollution and mortality may show a better correlation due to decreased influence of the moderate weather on air pollution levels and health effects, as compared to the hot tropical or cold polar weather types. Past research has found such relationships between air pollution and mortality even at low pollution concentrations (Burnett et al., 1998; Schwartz and Dockery, 1992; Smoyer et al., 2000), with mortality being affected by background air pollution, even when stressful weather and air pollution levels were not present (Smoyer et al., 2000).

The high RR estimates within MT and DT air in the springtime highlight the response of individuals to early-season (springtime) stressors (Kalkstein and Smoyer, 1993). These stressors are due to the change in weather and/or increases in air pollution – as highlighted by the significantly higher RR estimates – in both DT and MT air in the spring. When sharp springtime changes in stressful weather occurs, non-acclimatized individuals become more vulnerable to the weather conditions rather than to air pollution, as is common in the eastern U.S. (Smoyer et al., 2000) and found to extend to southern Ontario and Quebec (Kalkstein and Smoyer, 1993). The transitional weather type resulted in similar health effects for all seasons, where the very quick changes in atmospheric pressure and inclement weather can be negative to human health (McGregor, 1999; Vanos and Cakmak, 2013). Although the TR weather type displayed the least modification

of RR by age and season, it should not be ignored, as this weather type has been linked to serious health effects such as ischaemic heart disease, myocardial infarction, stroke, and death (Feigin et al., 2000).

Within the wintertime cold and moist MP air, the greatest loss of human life due air pollution was found, even though significantly lower concentrations of NO₂ and O₃ were present. These results were similarly found in an SSC study in Seoul and Incheon, Korea for daily mortality from 1995 to 2009 (Kalkstein and Sheridan, 2011). They found an increased mortality response under the MP weather type, although air pollution levels were lower on MP as compared to DP days. Within the current study, we further noted this lower risk to be consistent among all age groups; however, the remaining seasons indicated moderate to significant age-modification of RR during MP and DP weather due to CO, NO₂ and SO₂ (Fig. 4). Hence, warnings for the elderly for these air masses would differ in the various seasons. With cold-related mortality being very high across Canada, the effect of cold weather on mortality may play a greater role in public health decisions.

The long-term additive effects of air pollution on human health should not be ignored (Smoyer et al., 2000). Canadian projections show that the severity and duration of air pollution episodes will increase as a result of a warmer climate, with levels predicted to increase the most in Windsor, Montreal, Toronto, Vancouver, Calgary, Edmonton, and Winnipeg (Seguin and Berry, 2008). This study has identified the pollutants and weather types to which the elderly are most susceptible, and signifies a new avenue for providing targeted air pollution–mortality prevention efforts based on predictions of incoming synoptic weather patterns.

4.3. Unanswered questions and future research

The current study has controlled for the full effects of weather on the air pollution–mortality associations in five age categories and four seasons. A study of this nature has not previously been completed, and greatly adds to the research literature, particularly for Canada. It is suggested that further differentiation by city be completed due to the variable concentrations and RR results. This can provide city-specific results and more targeted guidelines for environmental public health officials.

We highlight how the impacts of weather and air pollution work synergistically to impact human mortality; however, the exact magnitude of the effect modification due to weather or air pollution is unclear, particularly for the hottest weather types. Further exploration within each weather type can be completed to determine the relative magnitudes of either air pollution or weather as the greater factor associated with death. For example, assessing whether or not the mean mortality increases, decreases, or remains stable with increasingly polluted air (Kalkstein, 1995; Smoyer et al., 2000). Future inclusion of the irritating pollutant TSP is also vital, since it is significantly related to mortality (Schwartz, 2004), and has been linked to increased respiratory symptoms, decreased lung function, aggravated asthma, irregular heartbeat, and heart attacks (Kreyling et al., 2006). TSP has been also found to follow trends similar to those of SO₂, as well as O₃ (Greene et al., 1999; Portier et al., 2010; Smoyer-Tomic et al., 2003).

The time lags for health effects due to warm and cold weather, and air pollutants can also be assessed (e.g., Anderson and Bell (2009), Diaz et al. (2002a,b), Rainham et al. (2005), and Sheridan and Kalkstein (2010)). The human health response to cold exposure can show lag effects of up to two weeks (Hajat et al., 2007), as compared to 0–3 day lags found in the case of heat (Anderson and Bell, 2009; Sheridan and Kalkstein, 2010), yet less is known concerning the lag effects due to specific air pollutants. Health effects due to exposure to air pollution are cumulative, and have been found to nonlinearly affect health for many days after

exposure (Braga et al., 2001; Dominici et al., 2006; Zanobetti et al., 2008). A further study addressing the lag structures of health outcomes could generate significant results for air mass-pollution interactions, as well as multi-pollutant interactions, particularly in cold weather where lags effects may be longer.

5. Conclusions

The objective of this study was to investigate the air pollution–mortality relationship within synoptic weather types, and determine which combination of atmospheric conditions may pose increased health threats in the elderly age categories. This study is the first SSC-based epidemiological study completed in Canada. Daily changes in atmospheric composition were shown to affect the association of individual air pollutants and mortality, with risk estimates commonly significantly greater for elderly age groups. The ozone-mortality association was modified to the greatest extent by weather type, with O₃-related risks significantly increased in the hot and harmful DT and MT weather types. In all combined weather types, risk of mortality due to air pollution increased with age category for all pollutants but O₃. This shows the greater vulnerability of the elderly to the remaining pollutants (CO, NO₂ and SO₂) in all weather types. Overall, age was the most important modifier of the RR estimates, followed by weather type, with season resulting in the lowest amount of risk modification. Therefore efforts should be concentrated on the specific health impacts to each age group under individual weather types.

These results underscore the importance of providing appropriate and advanced air quality/weather warnings. Forecasting of synoptic weather can be useful in revealing future situations harmful to human health, and improve the specificity of estimating the relative risk of mortality due to air pollutants under atmospheric conditions that are unique to the city and time of year. The epidemiological evidence provided here also calls for the advancement of interdisciplinary research in Canadian environmental health science and policy to address specific population vulnerabilities and scientific knowledge gaps.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at <http://dx.doi.org/10.1016/j.envres.2013.08.003>.

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