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Synoptic weather types and aeroallergens modify the effect of air pollution on hospitalisations for asthma hospitalisations in Canadian cities

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ABSTRACT

Pollution levels and the effect of air pollution on human health can be modified by synoptic weather type and aeroallergens. We investigated the effect modification of aeroallergens on the association between CO, O_3, NO_2, SO_2, PM_{10}, $PM_{2.5}$ and asthma hospitalisation rates in seven synoptic weather types. We developed single air pollutant models, adjusted for the effect of aeroallergens and stratified by synoptic weather type, and pooled relative risk estimates for asthma hospitalisation in ten Canadian cities. Aeroallergens significantly modified the relative risk in 19 pollutant-weather type combinations, reducing the size and variance for each single pollutant model. However, aeroallergens did not significantly modify relative risk for any pollutant in the DT or MT weather types, or for PM_{10} in any weather type. Thus, there is a modifying effect of aeroallergens on the association between CO, O_3, NO_2, SO_2, $PM_{2.5}$ and asthma hospitalisations that differs under specific synoptic weather types.

1. Background

Associations between individual climatological variables, such as temperature, and human health outcomes have been well studied, and while this approach can draw meaningful associations between weather predictors and mortality or morbidity, it can fail to capture the complex effects of interrelated weather factors on human health outcomes. To account and understand how humans respond to a combination of meteorological variables simultaneously, spatial synoptic classification (SSC) can be used to group weather patterns using a suite of meteorological parameters into distinct categories (Sheridan, 2002). The SSC is becoming more widely used to investigate associations between pollutant levels and mortality; for example, a study based in North Carolina, USA found that ozone in conjunction with dry tropical (DT) and moist tropical (MT) weather types increased the risk of hospitalisation for asthma and myocardial infarction (Hanna et al., 2011).

Synoptic weather patterns have been found to affect concentrations of air pollutants (Davis et al., 2010; Greene et al., 1999; Rainham et al., 2005); however, the implications for human health are not clear. One study looked at 19 years of data for Toronto, finding no systematic modification of the pollution–mortality association by weather type but observing that variation in pollutant concentrations was in part dependent on the synoptic category (Rainham et al., 2005). Weather types can affect human health outcomes in their own right due to their intrinsic meteorological characteristics: the so called “offensive” SSCs, DT, dry tropical, and MT, moist tropical, have been found to increase mortality rates, and this effect increases with the duration of exposure to the weather type (Kyselý, 2007; Sheridan and Kalkstein, 2010).

Our recent work has found that air pollution modifies the effect of aeroallergens on asthma, increasing the rate of hospitalisations on days of high air pollution (Cakmak et al., 2012). These findings are consistent with both animal model and human studies that suggest biological interactions between pollutants and aeroallergens (Farraj et al., 2006; Kehrl et al., 1999; Peden, 2001; Whitekus et al., 2002). Airways damaged by air pollutants may be more susceptible to allergen exposure (Amato et al., 2010), while

Abbreviations: PM_{10}, Particulate matter with a median aerodynamic diameter less than or equal to 10 μm; $PM_{2.5}$, Particulate matter with a median aerodynamic diameter less than or equal to 2.5 μm; AIC, The Akaike Information Criterion; SSC, Spatial Synoptic Classification.

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population level studies support an interactive effect between pollution and aeroallergens, without suggesting a causal mechanism (Atkinson and Strachan, 2004; Johnston and Sears, 2006).

There is some evidence that aeroallergen levels can be increased by synoptic weather conditions such as low height and stability in the nocturnal boundary layer (Gassmann and Gardiol, 2007) or low surface pressures (Hart et al., 2007). The relationship between pollution, aeroallergens, and asthma is therefore complex, and there is potential for further modification of this relationship by weather type, due to intrinsic characteristics of the weather type itself that can directly affect human health or by affecting pollutant and aeroallergen levels.

Forecasting that incorporates synoptic conditions, aeroallergen levels and air pollutants could be useful for managing the respiratory health of susceptible populations (Hondula et al., 2013; Jamason et al., 1997). Health officials can be warned of the potential for increased admissions and at-risk individuals can take measures to mitigate their risk of respiratory exacerbations (Lee et al., 2012). In this study we explore the relative risk of asthma hospitalisation from single air pollutants and the modifying effect of aeroallergens, pooled for ten cities to obtain an overall risk estimate for Canada, in the presence of seven synoptic scale weather types. The study design tests the association between daily changes in aeroallergens and asthma hospitalisations, where changes in asthma hospitalisations can only be contributed by individuals with susceptibility to aeroallergens; members of the population that are not susceptible to aeroallergens would therefore not be considered.

2. Methods

The study population comprised hospitalisations where asthma was recorded as the principal reason for admission, obtained from the Canadian Institute for Health Information (CIHI), for ten cities across Canada for which aeroallergen data were also available: Calgary, Edmonton, Halifax, London, Ottawa, Saint John, Toronto, Vancouver, Windsor, and Winnipeg. Data were obtained for the period April 1, 1994, to March 31, 2007, with city population data centred on 2000. Asthma hospitalisations were coded 493 or J45 and J46 by using the International Classification of Disease, 9th or 10th revision (http://www.who.int/classifications/icd/en/).

Air pollution data for each city were obtained from the National Air Pollution Surveillance (NAPS) network as one hour maximum daily ozone concentrations, 24 h concentrations of carbon monoxide, nitrogen dioxide, and sulphur dioxide, and particulate matter with mean aerodynamic diameters of 10 (PM_{10}) and 2.5 μm ($PM_{2.5}$).

Aeroallergens were collected by Aerobiology Research Laboratories, using a standardised method for all cities for the study period of April to October, 1994 to 2007. Rotational impact methods were used to obtain 24 h collections of pollen grains and fungal spores and estimate the number of particles present per cubic meter of air sampled. Aeroallergens show large day to day variations and therefore we log transformed the data for analysis.

Spatial Synoptic Classification combines routinely collected meteorological variables (air temperature, dew point, wind velocity, pressure, and cloud cover) in order to classify a weather situation into one of six weather types, dry moderate (DM), dry polar (DP), dry tropical (DT), moist moderate (MM), moist polar (MP), moist tropical (MT), plus a transition category (TR) where one weather type transitions into a different type. MT+ (moist tropical plus) and MT++ occur rarely in Canada, and when found were classified into the MT. The SSC is a semi-automated classification system (2002) developed and maintained by Sheridan (http://sheridan.geog.kent.edu/ssc.html). The data used for classification are obtained from the Meteorological Service of Canada from airport weather stations in each of the ten cities. Daily synoptic weather classifications for each city are available at the SSC archive.

Generalised additive models (S-Plus, Professional Edition Version 6.0.2 (1) for Microsoft Windows; Insightful Corp, Seattle, Wash) with stringent convergence criteria ($\varepsilon < 10-14$) were used to test the association between asthma hospitalisations and individual pollutants, adjusting for the modifying effect of aeroallergens. Each model was developed for days corresponding to one of seven synoptic scale weather types. We assumed that the hospitalisation data was Poisson-distributed. The effect of each pollutant on asthma hospitalisation was tested for the day of admission and five days preceding admission (lags 0, 1, 2, 3, 4, 5), selecting the lag period which optimised the observed effect size. Relative risks were estimated for an interquartile increase (25th to 75th) in hospitalisation for asthma, stratified by weather type. The relative risks of asthma hospitalisation for each pollutant were tested with and without adjustment for the effect of aeroallergens for days in the presence of each weather type.

The model can be summarised as follows:

$$LogE(Y_t / X_t, Z_t) \sim \beta X_{t-l} + \delta Z_{t-l} + \text{ns(time, knot)} + DOW_t$$

Where Y_t is the daily count of hospital asthma admissions, X_{t-l} is the pollutant level on day t with 0–5 days of lag, Z_{t-l} is the aeroallergen level on day t with 0–5 days of lag, β and δ are the regression coefficients linking the pollutant and the aeroallergen to daily asthma hospitalisations, respectively, ns(time, knot) is the natural spline of time with knots at 13, 25, 49 and 145 days of observation, the number of knots selected based on minimization of Akaike's Information Criterion (AIC) and the Bartlett test for autocorrelation; and DOW_t is an indicator for the day of the week on time t. Effect estimates for each pollutant, adjusted and unadjusted for aeroallergens, in each weather type were obtained by replacing β by $\beta_{(dm)}I_{dm}$, where I_{dm} is an indicator of the DM weather type (Vanos et al., 2014).

Data was pooled for the ten cities using a random effects model with a random intercept to account for between-city inhomogeneity, and the effect estimates were weighted using the inverse sum of within and between-city variance, as in Cakmak et al. (2012). Single-pollutant-specific regression coefficients were combined using the restricted maximum likelihood method. A t-test was used to test for significant differences ($P < 0.05$) in RR before and after adjustment by aeroallergens for each single-pollutant model within each weather type.

Table 1
Weather type frequency (%) per city and the average frequency for all cities during the study period, for seven weather types: DM (dry moderate), DP (dry polar), DT (dry tropical), MM (moist moderate), MP (moist polar), MT (moist tropical), and TR (transitional). NA indicates that weather type not present.

	DM	DP	DT	MM	MP	MT	TR
Calgary	31	23	3	9	19	1	8
Edmonton	21	32	2	8	22	1	12
Halifax	23	18	1	18	13	8	9
London	27	11	4	19	7	20	8
Ottawa	29	11	5	21	9	14	9
Saint John	18	13	NA	21	26	6	11
Toronto	34	8	7	17	5	18	10
Vancouver	44	3	NA	28	13	1	9
Windsor	26	12	5	18	5	23	7
Winnipeg	27	16	2	16	13	12	11
All-city average	28	15	3	17	13	10	10

Table 2
Asthma admissions per 100,000 city population (and standard deviation), and the average rate of admissions for all cities during the study period, for seven weather types: DM (dry moderate), DP (dry polar), DT (dry tropical), MM (moist moderate), MP (moist polar), MT (moist tropical), and TR (transitional). NA indicates that there is not enough data to calculate standard deviation.

City	Weather type						
	DM	DP	DT	MM	MP	MT	TR
Calgary	316.6 (13.3)	276.5 (11.6)	27.1 (3.4)	87.3 (6.9)	221.5 (11.5)	2.5 (2.3)	87.1 (7.1)
Edmonton	199.4 (9.7)	307.1 (11.7)	18.9 (3.3)	84.1 (6.2)	212.9 (10.8)	2.5 (1)	126.2 (7.8)
Halifax	NA	392.6 (12.7)	4.4 (1.2)	250.3 (9)	434.1 (13.1)	47.2 (2.9)	188.4 (8.2)
London	169.6 (5.2)	108.1 (3.7)	19.3 (2.2)	113.4 (3.8)	122.3 (4.5)	63.1 (3.1)	81.2 (4.1)
Ottawa	162.7 (8.5)	173.8 (7.4)	16.2 (2.1)	117.5 (7.8)	105.1 (6.2)	32.7 (3.1)	78.8 (5.1)
Saint John	73.7 (2)	150.8 (3.3)	0.7 (0)	146.1 (2.9)	NA	22.5 (1.6)	132.4 (2.8)
Toronto	337 (46.1)	181 (34.2)	33.5 (11.5)	184.2 (35.6)	178.2 (33.6)	80.3 (20.3)	133 (27.3)
Vancouver	208 (15.4)	35.5 (7.3)	NA	307.2 (20.2)	226 (17.9)	14.3 (3.9)	88.6 (10.2)
Windsor	NA	275.7 (10.1)	39.2 (3.4)	237.5 (10)	192.3 (8.5)	NA	142.6 (7.2)
Winnipeg	229 (9.8)	305 (10.7)	16.4 (2.8)	166.2 (8.1)	198 (8.6)	36 (3.2)	127.7 (6.8)
All-city average	169.6	220.6	17.6	169.4	189	30.1	118.6

Table 3
Mean (and standard error) concentrations of aeroallergens (counts/m^2) by city for the study period of April to October, 1994 to 2007. DM: dry moderate; DP: dry polar; DT: dry tropical; MM: moist moderate; MP: moist polar; MT: moist tropical; TR: transitional weather types. NA indicates that there is not enough data to calculate standard error.

City	Allergen	Weather type						
		DM	DP	DT	MM	MP	MT	TR
Calgary	Basidiomycetes	279 (16)	275 (25)	295 (34)	383 (37)	242 (33)	366 (256)	241 (23)
Edmonton	Basidiomycetes	356 (25)	423 (24)	149 (36)	419 (46)	579 (70)	427 (190)	449 (39)
Halifax	Basidiomycetes	450 (31)	260 (29)	843 (167)	277 (26)	152 (20)	382 (49)	308 (48)
London	Basidiomycetes	753 (31)	332 (27)	502 (76)	592 (33)	294 (29)	865 (53)	482 (40)
Ottawa	Basidiomycetes	920 (41)	443 (38)	767 (108)	976 (62)	439 (53)	1344 (87)	745 (60)
Saint John	Basidiomycetes	544 (45)	268 (42)	11 (1)	754 (59)	323 (26)	824 (155)	642 (73)
Toronto	Basidiomycetes	511 (22)	206 (19)	469 (39)	474 (33)	266 (39)	642 (35)	482 (41)
Vancouver	Basidiomycetes	337 (14)	238 (44)	NA	346 (17)	308 (24)	271 (49)	274 (31)
Windsor	Basidiomycetes	569 (26)	244 (23)	553 (46)	481 (27)	256 (30)	686 (42)	331 (26)
Winnipeg	Basidiomycetes	478 (29)	229 (18)	349 (72)	747 (56)	442 (48)	648 (46)	445 (37)
Calgary	Ascomycetes	163 (9)	319 (18)	168 (32)	546 (66)	419 (25)	108 (21)	222 (22)
Edmonton	Ascomycetes	244 (18)	369 (22)	136 (27)	645 (59)	770 (41)	953 (331)	391 (37)
Halifax	Ascomycetes	160 (9)	116 (9)	206 (40)	336 (32)	211 (19)	232 (35)	272 (28)
London	Ascomycetes	264 (14)	159 (15)	154 (19)	711 (43)	389 (38)	549 (37)	587 (57)
Ottawa	Ascomycetes	294 (14)	191 (14)	239 (19)	964 (49)	463 (37)	767 (61)	654 (49)
Saint John	Ascomycetes	306 (26)	297 (32)	267 (247)	322 (21)	381 (28)	354 (43)	363 (35)
Toronto	Ascomycetes	218 (11)	115 (9)	229 (28)	562 (31)	353 (53)	453 (26)	494 (37)
Vancouver	Ascomycetes	138 (5)	129 (18)	NA	287 (14)	314 (19)	147 (21)	283 (30)
Windsor	Ascomycetes	290 (16)	158 (13)	219 (21)	725 (41)	312 (31)	707 (42)	518 (41)
Winnipeg	Ascomycetes	302 (16)	170 (13)	153 (42)	906 (58)	583 (45)	646 (55)	465 (38)
Calgary	F. imperfecti	1231 (54)	1187 (55)	1157 (110)	1694 (124)	1039 (56)	1959 (1021)	1095 (84)
Edmonton	F. imperfecti	1867 (113)	1646 (68)	1389 (296)	1988 (202)	1836 (113)	1726 (585)	1643 (116)
Halifax	F. imperfecti	739 (42)	419 (28)	1169 (337)	1030 (69)	588 (60)	1150 (110)	724 (65)
London	F. imperfecti	1783 (84)	771 (59)	1450 (299)	2124 (126)	777 (61)	3219 (185)	1941 (207)
Ottawa	F. imperfecti	1710 (84)	746 (64)	1666 (213)	3415 (197)	1266 (143)	3849 (290)	2075 (159)
Saint John	F. imperfecti	894 (52)	483 (56)	26 (8)	1197 (65)	644 (33)	1229 (142)	1073 (100)
Toronto	F. imperfecti	1395 (62)	548 (46)	2166 (179)	2102 (198)	837 (87)	2584 (167)	1699 (133)
Vancouver	F. imperfecti	677 (24)	592 (96)	NA	864 (33)	834 (42)	482 (87)	685 (50)
Windsor	F. imperfecti	1927 (90)	632 (36)	2479 (195)	2230 (118)	885 (86)	3452 (172)	1822 (176)
Winnipeg	F. imperfecti	2072 (86)	954 (57)	1249 (205)	2999 (157)	1237 (76)	3535 (237)	1899 (141)

3. Results

The frequency of occurrence of the seven weather types during the study period is presented in Table 1. The Canadian cities used in this study are spread across a large region and experience a varied climate, with some notable national and regional trends. The dry moderate (DM) and moist moderate (MM) weather types are the most frequent across all cities, while the least common were the dry tropical (DT) and moist tropical (MT) weather types. Regionally, the dry polar (DP) weather type was most common in the prairies and on the East Coast and least frequent in Toronto and Vancouver.

Asthma admission rates per 100,000 varied by weather type and city (Table 2). Rates of admission were lowest in the DT and MT weather types, at 17.6 and 30.1 per 100,000 respectively for all cities. The highest all city admission rate was recorded for the DP weather type, at 220.6 admissions per 100,000, although this varied from a low of 35.5 in Vancouver to 392.6 in Halifax. The highest individual city rate of admissions for asthma was recorded in Halifax, at 434.1 per 100,000 in the MP weather type.

Aeroallergen levels varied between cities and by weather type (Table 3.). Basidiomycetes spore concentrations were highest in Ottawa in MM, DT, DM, and MT weather types and lowest in all cities in the DP weather type. Concentrations ranged from 4.83 counts in Edmonton in the DT weather type to 1343 counts in Ottawa in the MT type. Ascomycetes concentrations ranged from 9.05 grains/m^3 in Halifax in DP to 1418 in Ottawa in the MM weather type. Fungi imperfecti concentrations ranged from 5.59 grains/m^3 in Halifax in the DP weather type, to 4389.3 grains/m^3 in Ottawa in the MT type. For all three fungal aeroallergens, means were clustered most tightly in the DP weather type.

Table 4
Mean (and standard error) concentrations of aeroallergens (counts/m^2) by city for the study period of April to October, 1994 to 2007. DM: dry moderate; DP: dry polar; DT: dry tropical; MM: moist moderate; MP: moist polar; MT: moist tropical; TR: transitional weather types. NA indicates that there is not enough data to calculate standard error.

City	Allergen	Weather type						
		DM	DP	DT	MM	MP	MT	TR
Calgary	Weeds	10.7 (0.6)	5.8 (0.5)	10.2 (1.3)	7.2 (0.8)	3.3 (0.3)	10.3 (4.2)	7.6 (1)
Edmonton	Weeds	19.3 (2)	13 (1.6)	8.7 (3.5)	16.1 (3.2)	9.5 (1.3)	17.4 (9.5)	21.1 (3.3)
Halifax	Weeds	2.9 (0.2)	2.1 (0.2)	3.8 (0.8)	1.6 (0.2)	1.1 (0.2)	2.6 (0.3)	2.2 (0.2)
London	Weeds	11 (0.6)	6.1 (0.7)	11.6 (1.3)	7.9 (0.6)	4 (0.7)	15.7 (1.1)	8 (1)
Ottawa	Weeds	11.8 (0.7)	6.1 (0.9)	15.8 (2.1)	9.7 (0.8)	3.8 (0.8)	16.2 (1.6)	12.8 (1.8)
Saint John	Weeds	2.5 (0.2)	1.6 (0.2)	NA	2.3 (0.2)	2.5 (0.3)	2.4 (0.3)	2.7 (0.3)
Toronto	Weeds	8.1 (0.4)	4.7 (0.6)	12.1 (1)	6.7 (0.8)	3 (0.7)	10.1 (0.7)	9.8 (0.9)
Vancouver	Weeds	5.3 (0.3)	6.1 (2)	NA	4 (0.3)	2.7 (0.3)	12.1 (2.5)	5.3 (0.6)
Windsor	Weeds	13.6 (0.7)	8.3 (0.7)	19.6 (1.8)	10.6 (0.6)	4.9 (1)	17.8 (1)	10.7 (1.2)
Winnipeg	Weeds	15.3 (1)	10.7 (1.1)	14.4 (3.8)	13 (1)	6.8 (1.3)	27 (2.1)	15.3 (1.7)
Calgary	Trees	31.8 (3)	28.8 (2.9)	22.6 (5.1)	32.5 (4.6)	23.4 (3.6)	73 (37.5)	48.1 (7.3)
Edmonton	Trees	23 (3.9)	20.2 (2.2)	32.6 (8.7)	18.1 (3.5)	11.1 (1.9)	23.3 (15.8)	15.9 (2.1)
Halifax	Trees	51.2 (7.3)	35.1 (5)	86.5 (47.8)	13.6 (6)	13.9 (3.5)	54.8 (18.5)	47.6 (8.8)
London	Trees	26.9 (2.9)	19.7 (3.8)	50.9 (8.6)	13.9 (2)	16.4 (3.6)	23.9 (4.6)	28.2 (5.2)
Ottawa	Trees	42.3 (5.2)	30.5 (3.8)	94.2 (16)	25.8 (4.5)	14.7 (2.6)	44.7 (8)	65.1 (13.4)
Saint John	Trees	15.4 (3.1)	37.7 (9.7)	12 (12)	38.8 (12.1)	34.5 (3.9)	15.2 (6.1)	71.2 (22.1)
Toronto	Trees	28.4 (4.2)	22.6 (3.7)	50 (10.5)	26.4 (3.7)	25 (9.6)	21.5 (4.3)	34.7 (6.4)
Vancouver	Trees	123 (15.4)	70.1 (21.3)	NA	126 (11.4)	78.7 (11.3)	142 (33.2)	120 (15.4)
Windsor	Trees	32.8 (5.3)	17.9 (2.8)	44.4 (9.9)	17.3 (2.6)	20.6 (7.7)	22.5 (5.6)	24.3 (5.2)
Winnipeg	Trees	40.4 (6.1)	14 (2.7)	30.1 (6.3)	16.8 (6.1)	12.6 (3)	13 (3.2)	15.4 (3.9)
Calgary	Grasses	7.8 (0.6)	7.8 (0.6)	7.2 (1.5)	9.6 (1.1)	4.1 (0.5)	14.2 (6.4)	14.8 (2.5)
Edmonton	Grasses	12.8 (2.1)	14.2 (1.3)	7 (2.2)	15.6 (4.7)	7.5 (0.9)	24.7 (8.8)	17.9 (2.5)
Halifax	Grasses	8.1 (0.9)	3.9 (0.5)	7.6 (3.4)	3.2 (0.4)	1.8 (0.3)	6 (0.9)	6.3 (0.9)
London	Grasses	10.6 (1)	10.8 (1.9)	14.9 (4.2)	9 (1.2)	6.8 (1.2)	14 (1.9)	7.5 (1.2)
Ottawa	Grasses	15.9 (1.9)	22.9 (6.6)	13 (2)	11.4 (1.5)	10.2 (2.6)	23.5 (3.1)	19.3 (4.7)
Saint John	Grasses	4.1 (0.5)	3.7 (0.6)	NA	4.1 (0.5)	4.1 (0.4)	2.6 (0.6)	4.4 (0.6)
Toronto	Grasses	9.6 (0.7)	13 (2.1)	19.7 (2.6)	9.3 (1.2)	8.4 (2.2)	13.1 (1.3)	9.7 (1.2)
Vancouver	Grasses	11.7 (0.7)	9.4 (2)	NA	8 (0.6)	6.6 (0.8)	17.1 (4.8)	12 (2)
Windsor	Grasses	12.9 (1.1)	10.2 (1.1)	28.2 (3.7)	12 (1.4)	10.2 (2.6)	17.8 (2.3)	12.5 (1.7)
Winnipeg	Grasses	10.8 (1.1)	9.8 (1.6)	7.7 (3.4)	10.2 (1.4)	5.9 (0.9)	17.9 (2)	10.2 (1.8)

Table 5
Mean (and standard error) concentrations of pollutants (ppb) by city for the study period of April to October, 1994 to 2007. DM: dry moderate; DP: dry polar; DT: dry tropical; MM: moist moderate; MP: moist polar; MT: moist tropical; TR: transitional weather types. NA indicates that there is not enough data to calculate standard error.

City	Pollutant	Weather type						
		DM	DP	DT	MM	MP	MT	TR
Calgary	CO	0.52 (0.01)	0.49 (0.01)	0.57 (0.02)	0.5 (0.01)	0.47 (0.01)	0.51 (0.06)	0.46 (0.01)
Edmonton	CO	0.42 (0.01)	0.41 (0.01)	0.44 (0.02)	0.41 (0.01)	0.37 (0.01)	0.43 (0.04)	0.39 (0.01)
Halifax	CO	0.56 (0.01)	0.48 (0.01)	0.52 (0.06)	0.59 (0.01)	0.57 (0.01)	0.61 (0.03)	0.52 (0.01)
London	CO	0.23 (0.01)	0.21 (0.02)	0.21 (0.03)	0.22 (0.02)	0.21 (0.02)	0.23 (0.02)	0.32 (0.03)
Ottawa	CO	0.49 (0.01)	0.42 (0.01)	0.7 (0.04)	0.54 (0.01)	0.44 (0.01)	0.57 (0.02)	0.5 (0.02)
Saint John	CO	0.65 (0.02)	0.65 (0.02)	0.91 (0.11)	0.56 (0.01)	0.64 (0.02)	0.52 (0.03)	0.55 (0.02)
Toronto	CO	0.83 (0.02)	0.83 (0.03)	0.81 (0.03)	0.84 (0.02)	0.83 (0.04)	0.84 (0.02)	0.77 (0.03)
Vancouver	CO	0.52 (0.01)	0.44 (0.01)	NA	0.52 (0.01)	0.5 (0.01)	0.61 (0.04)	0.47 (0.01)
Windsor	CO	0.51 (0.02)	0.4 (0.02)	0.55 (0.04)	0.54 (0.02)	0.45 (0.03)	0.54 (0.02)	0.47 (0.03)
Winnipeg	CO	0.45 (0.01)	0.41 (0.01)	0.48 (0.02)	0.43 (0.01)	0.36 (0.01)	0.46 (0.01)	0.4 (0.01)
Calgary	O_3	43.9 (0.3)	38.8 (0.4)	48.6 (1.2)	37.8 (0.5)	31.1 (0.4)	48.3 (6.1)	41.9 (0.7)
Edmonton	O_3	46.6 (0.6)	38.3 (0.4)	51.3 (1.7)	37.9 (0.7)	31.6 (0.5)	50.4 (4.7)	41.4 (0.8)
Halifax	O_3	33.9 (0.6)	30.8 (0.5)	43.5 (2.6)	34.2 (0.7)	32.3 (0.5)	37.3 (1.4)	36.9 (0.8)
London	O_3	52.5 (0.7)	41 (0.7)	69.7 (2)	45.5 (0.7)	35.8 (0.7)	65.2 (1)	46.7 (1.1)
Ottawa	O_3	38.8 (0.4)	33 (0.5)	57.5 (1.3)	36 (0.5)	30.4 (0.6)	49.2 (0.9)	40.7 (0.8)
Saint John	O_3	36.3 (0.6)	37.3 (0.6)	38 (1.5)	35.6 (0.5)	35.8 (0.4)	36.2 (1.5)	36 (0.7)
Toronto	O_3	46.7 (0.5)	35.6 (0.5)	71.7 (1.5)	41 (0.7)	31.5 (0.8)	59.1 (0.9)	44.9 (0.8)
Vancouver	O_3	35.9 (0.3)	34.6 (0.7)	NA	29 (0.3)	27.1 (0.4)	45.3 (2.6)	34.3 (0.5)
Windsor	O_3	54.4 (0.7)	39.8 (0.4)	74.7 (1.6)	43.1 (0.7)	30.9 (0.6)	63.1 (0.9)	43.2 (0.9)
Winnipeg	O_3	38.5 (0.4)	32.8 (0.4)	51.5 (1.4)	31.9 (0.5)	27 (0.4)	41.3 (0.6)	33.7 (0.6)
Calgary	NO_2	19.4 (0.2)	18.3 (0.2)	21.5 (0.6)	17.4 (0.4)	16.4 (0.2)	20.4 (1.3)	16.7 (0.4)
Edmonton	NO_2	17.8 (0.3)	16.9 (0.2)	18.4 (1)	16.2 (0.4)	13.5 (0.2)	18.7 (1.8)	15.8 (0.4)
Halifax	NO_2	14.5 (0.4)	13.9 (0.4)	14.1 (1)	14.9 (0.4)	14.6 (0.5)	14.3 (0.7)	13.1 (0.6)
London	NO_2	13.8 (0.3)	11 (0.4)	18.8 (1)	11.9 (0.3)	11.1 (0.4)	13.2 (0.3)	11.9 (0.5)
Ottawa	NO_2	13.9 (0.3)	11.1 (0.3)	18.8 (0.8)	13.8 (0.3)	11 (0.4)	15.2 (0.5)	12.7 (0.5)
Saint John	NO_2	10.2 (0.3)	9.5 (0.3)	12.2 (5)	8.8 (0.2)	8.2 (0.2)	10.8 (0.6)	8.1 (0.3)
Toronto	NO_2	24.1 (0.3)	19.9 (0.4)	29.3 (0.7)	23.1 (0.4)	20.4 (0.6)	24.7 (0.4)	19.7 (0.4)
Vancouver	NO_2	16.5 (0.2)	14.3 (0.4)	NA	15.5 (0.1)	14.9 (0.2)	19.6 (1)	14.4 (0.3)
Windsor	NO_2	21.8 (0.4)	17.7 (0.4)	21.3 (0.8)	19.6 (0.4)	17.9 (0.5)	19 (0.4)	17.2 (0.5)
Winnipeg	NO_2	11.9 (0.2)	11.6 (0.2)	13.7 (0.8)	9.8 (0.2)	9 (0.2)	10 (0.3)	9.4 (0.2)

Regional differences were clearer for pollen counts, with the lowest values for weed pollen and grass pollen found consistently in Halifax and Saint John, on the East Coast, and the highest values for tree pollen in Vancouver on the West Coast (Table 4.). Weed pollen concentrations ranged from 27 counts/m^3 in Winnipeg in MT to 1.09 counts/m^3 in MP in Halifax. The highest concentration of tree pollen was found in Vancouver in MM, 180.5 counts/m^3, and the lowest in Edmonton in the MP weather type. Grass pollen concentrations were highest in Windsor in DT, at 61.3 counts/m^3, and lowest in Halifax and Saint John in all weather types.

Mean daily air pollutant levels varied by city and weather type, with regional differences also present (Table 5). CO concentrations ranged from 0.18 ppb in London DP weather to 0.96 ppb in Toronto in MM. In all seven weather types, the highest and lowest values were found in Toronto and London respectively; Halifax and Saint John tended to be toward the higher end of the range while the prairie cities Winnipeg, Edmonton, and Calgary, toward the lower, in all weather types. CO concentrations were not highly variable by weather type, however. Mean daily O_3 concentrations ranged from 27 ppb in Winnipeg in the MP weather type to 81.8 ppb in Windsor in DT. The highest values were in the Great Lakes cities of Windsor, Toronto, and London, in the DT and MT weather types. Mean values were least dispersed in DP and MP weather types, remaining low for all cities examined. NO_2 concentrations were highest in Toronto and Windsor in all weather types and lowest in Winnipeg and Saint John in all weather types. The highest mean concentration of NO_2, 29.3 ppb, was in Toronto in DT weather.

Mean concentrations of SO_2 ranged from 1.39 in Edmonton in the MP weather type to 14 ppb in Windsor in DT weather (Table 6). With the exception of the DT weather type, the highest mean concentrations of SO_2 were found in the East Coast cities Halifax and Saint John. Particulate matter concentrations ranged from 7.87 for PM_{10} in Vancouver in the MP weather type, to 48.6 particulates μg/m^3 in Windsor in MT. The effect of weather type is more apparent in $PM_{2.5}$, where mean particulate concentrations range from 2.62 in Halifax in the MP weather type, to 30 μg/m^3 in London in the MT weather type. $PM_{2.5}$ counts are lowest in the DP and MP weather types, and highest in the DT and MT weather types.

The single pollutant models found significant increases in relative risk for asthma hospital admissions due to air pollutants in the general population (Fig. 1), with the exception of PM_{10} in the DT weather type. After adjustment for the modifying effect of aeroallergens the relative risk of hospitalisation declined, but remained above 1.0 in all pollutants in all weather types, with the exception of O_3 and PM_{10}, both in the DT weather type.

Significant ($P \leq 0.05$) differences in relative risk of asthma hospitalisations from air pollutants after adjustment for the effect of aeroallergens were found for CO, O_3, NO_2, SO_2, and $PM_{2.5}$. There were no significant changes in RR after adjustment for aeroallergens in any weather type for PM_{10}, and no significant differences in RR in DT or MT weather types for any of the pollutants.

The adjustment for aeroallergens significantly decreased the effect size of air pollutants in 19 of the 42 cases (pollutant and weather type) examined. The largest modifying effect was found for CO, in the MP weather type, where the RR of asthma hospitalisation decreased after adjustment for aeroallergens from 1.282 (95% CI, 1.163–1.413) to 1.065 (95% CI, 1.032–1.098), and the second largest was for CO in the MM weather type, where RR decreased from 1.236 (95% CI, 1.158–1.32) to 1.059 (95% CI, 1.027–1.092). In the TR weather type, adjustment for aeroallergens decreased the effect size of NO_2 on asthma hospital admissions from 1.218 (95% CI, 1.125–1.319) to 1.055 (95% CI, 1.012–1.098).

The modifying effect of aeroallergens on air pollution was significant for SO_2 for the DM, DP, MM, MP, and TR weather types, with

Table 6
Mean (and standard error) concentrations of pollutants (ppb) by city for the study period of April to October, 1994 to 2007. DM: dry moderate; DP: dry polar; DT: dry tropical; MM: moist moderate; MP: moist polar; MT: moist tropical; TR: transitional weather types. NA indicates that there is not enough data to calculate standard error.

City	Pollutant	Weather type						
		DM	DP	DT	MM	MP	MT	TR
Calgary	SO_2	2.6 (0.1)	2.4 (0)	3.1 (0.2)	2.2 (0.1)	2 (0.1)	3 (0.6)	2.2 (0.1)
Edmonton	SO_2	2.2 (0.1)	2 (0.1)	2.1 (0.2)	1.7 (0.1)	1.4 (0.1)	2 (0.4)	1.6 (0.1)
Halifax	SO_2	7.3 (0.2)	8.5 (0.2)	7.6 (0.6)	6.9 (0.3)	7.1 (0.3)	6.3 (0.4)	7.4 (0.4)
London	SO_2	3.1 (0.1)	1.7 (0.1)	4.9 (0.3)	2.2 (0.1)	1.5 (0.1)	3.7 (0.2)	2.2 (0.2)
Ottawa	SO_2	2.4 (0.1)	2.1 (0.1)	3.3 (0.2)	2 (0.1)	2 (0.1)	2.2 (0.1)	2.2 (0.1)
Saint John	SO_2	9.2 (0.4)	6.9 (0.3)	14 (2.1)	7.2 (0.3)	5.9 (0.2)	8.9 (0.8)	7.1 (0.4)
Toronto	SO_2	3.8 (0.1)	2.7 (0.1)	5.3 (0.3)	3.2 (0.1)	2.5 (0.1)	4.4 (0.1)	3.3 (0.1)
Vancouver	SO_2	3.2 (0.1)	2.1 (0.1)	NA	2.6 (0.1)	2.1 (0.1)	3.8 (0.4)	2.5 (0.1)
Windsor	SO_2	7.4 (0.2)	5.4 (0.2)	9.5 (0.4)	5.9 (0.2)	4.8 (0.3)	6.7 (0.2)	5.8 (0.2)
Winnipeg	SO_2	NA	NA	NA	NA	NA	NA	NA
Calgary	PM_{10}	25 (1.9)	18.7 (1)	39.6 (4.7)	20.5 (1.9)	15.1 (0.8)	NA	17.9 (1.6)
Edmonton	PM_{10}	24.1 (1.9)	18.6 (1.2)	31.3 (4.4)	16.8 (1.1)	12.6 (0.9)	27.7 (2.4)	18.4 (1.9)
Halifax	PM_{10}	16 (0.9)	13.5 (0.7)	NA	16.6 (1.3)	9.7 (0.7)	18 (1.6)	13.9 (1.4)
London	PM_{10}	NA	NA	NA	NA	NA	NA	NA
Ottawa	PM_{10}	NA	NA	NA	NA	NA	NA	NA
Saint John	PM_{10}	17.3 (0.8)	13.8 (1.1)	NA	16 (1)	11.7 (0.6)	16.2 (1.6)	13.6 (0.9)
Toronto	PM_{10}	21.8 (0.6)	15.3 (0.7)	38 (2.2)	22.3 (0.9)	14.9 (1)	32.3 (1.2)	17.2 (1)
Vancouver	PM_{10}	15.1 (0.4)	11.2 (0.9)	NA	12.5 (0.4)	10.3 (0.5)	20.5 (3.7)	10.3 (0.7)
Windsor	PM_{10}	25.8 (1.6)	18.2 (1.1)	40.8 (5)	27.2 (1.3)	14.3 (1.2)	35.4 (2.7)	24.5 (2.7)
Winnipeg	PM_{10}	24 (1.1)	19.5 (1.2)	39.9 (2.4)	16.7 (0.9)	11.1 (0.8)	28.9 (2)	19.1 (1.4)
Calgary	$PM_{2.5}$	8.2 (0.4)	5.6 (0.2)	15.7 (2.2)	7.3 (0.3)	5.5 (0.2)	11.1 (1.6)	6.3 (0.4)
Edmonton	$PM_{2.5}$	9 (0.5)	6.2 (0.2)	11.1 (0.9)	6.8 (0.4)	4 (0.1)	12.8 (2)	6.6 (0.3)
Halifax	$PM_{2.5}$	6 (0.3)	3.1 (0.1)	10.8 (1.9)	5.9 (0.3)	2.6 (0.2)	11.4 (1.2)	5.1 (0.5)
London	$PM_{2.5}$	11.2 (0.4)	6.4 (0.3)	14.4 (1.3)	12.6 (0.6)	6.5 (0.3)	21.4 (0.9)	11.3 (0.8)
Ottawa	$PM_{2.5}$	6.6 (0.3)	3 (0.1)	12.9 (0.8)	7.8 (0.3)	3.4 (0.2)	14.5 (0.7)	7.6 (0.4)
Saint John	$PM_{2.5}$	8.8 (0.4)	6.8 (0.3)	NA	8.2 (0.5)	5.6 (0.3)	8.9 (0.8)	6.6 (0.4)
Toronto	$PM_{2.5}$	8.8 (0.2)	4.7 (0.2)	19.8 (1)	11 (0.4)	5.2 (0.3)	19.1 (0.6)	9 (0.4)
Vancouver	$PM_{2.5}$	6.4 (0.1)	4.1 (0.2)	NA	5 (0.1)	4.7 (0.2)	7.1 (0.8)	4.2 (0.2)
Windsor	$PM_{2.5}$	11 (0.4)	5 (0.2)	20.9 (1.3)	11.1 (0.4)	5.1 (0.3)	18.1 (0.6)	8.1 (0.5)
Winnipeg	$PM_{2.5}$	7.2 (0.2)	4.7 (0.1)	11.2 (0.6)	5.6 (0.2)	3.1 (0.1)	8.5 (0.4)	5.7 (0.3)

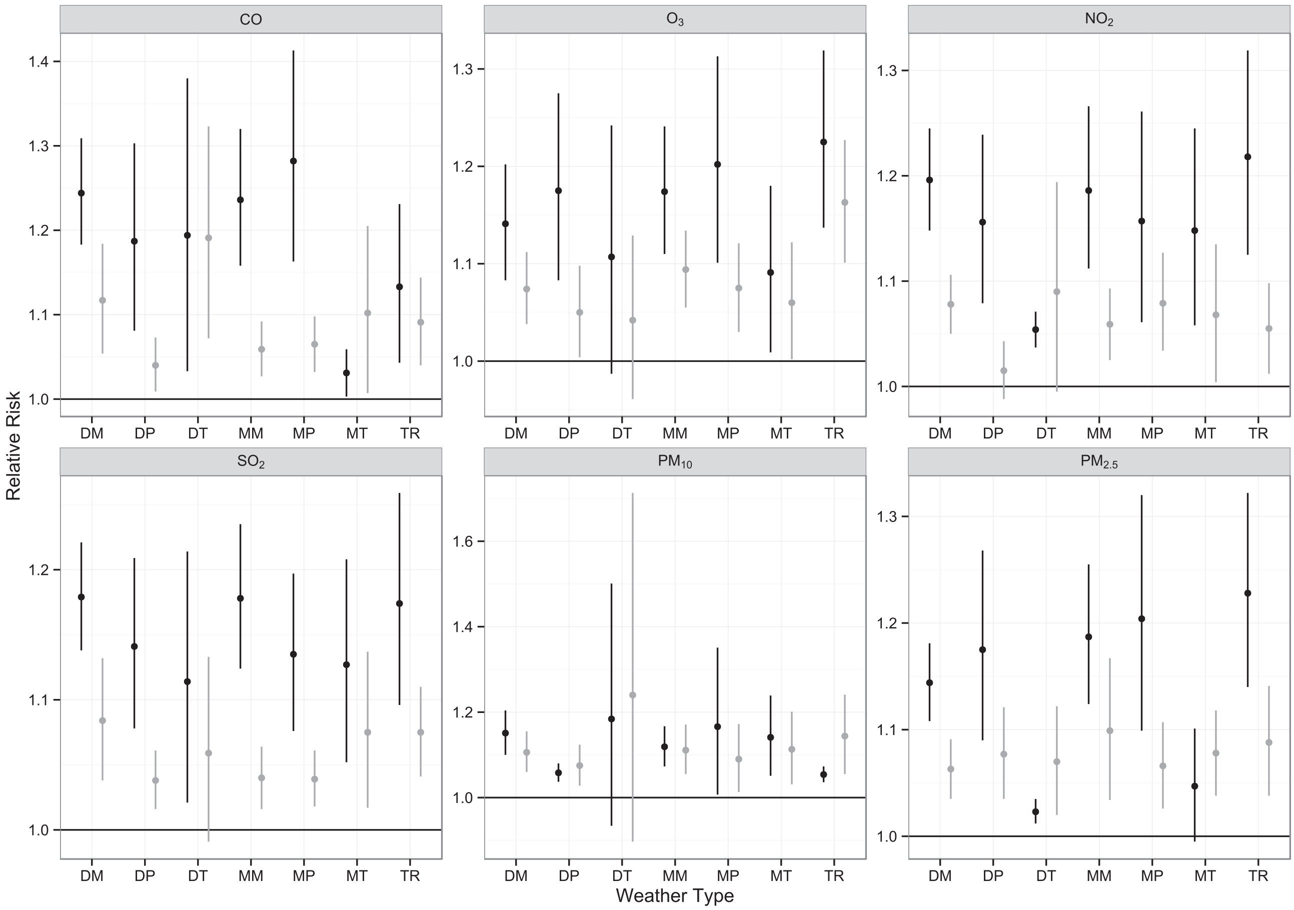

Fig. 1. Pooled estimates of relative risks of hospitalisation for asthma among ten cities, before (black) and after (grey) adjustment for aeroallergens. Bars represent 95% confidence intervals. DM: dry moderate; DP: dry polar; DT: dry tropical; MM: moist moderate; MP: moist polar; MT: moist tropical; TR: transitional weather types.

the largest difference after adjusting for the effect of aeroallergens in the MM weather type, from 1.178 (95% CI, 1.124–1.235 to 1.04 (95% CI, 1.016–1.064)); whereas for O_3 it was significant only in two of the weather types: DP, decreasing from 1.175 (95% CI, 1.083–1.275) in the unadjusted model to 1.05 (95% CI, 1.004–1.098) in the adjusted model, and in the MM weather type, from 1.174 (95% CI, 1.11–1.241)to 1.094 (95% CI, 1.055–1.134).

In the DP weather type, the effect estimate of pollutants on asthma hospitalisations was significantly decreased after adjustment for aeroallergens for all of the pollutants except $PM_{10,}$ with the largest decrease for CO and the smallest for $PM_{2.5}$, where RR went from 1.175 (1.09–1.268) to 1.077 (95% CI, 1.035–1.121).

4. Discussion

Pollutants exacerbate asthma (Islam et al., 2007; Peden, 2001; Strachan, 2000) and have been associated with increased emergency hospitalisations (Cheng et al., 2009; Tobías et al., 2004). Aeroallergens also exacerbate asthma both independently (Dales et al., 2004) and in interaction with air pollution (Burt and Sharma, 2002; Cakmak et al., 2012, 2014; Watanabe et al., 2011).

Our previous work (Cakmak et al., 2012) found an association between aeroallergens and asthma hospitalisations that was enhanced on higher pollution days. The present study also finds that in aeroallergens positively influence the relationship between air pollution and asthma, and that this modifying effect varies under the synoptic weather type present. This latter finding is consistent with a study of asthma admissions in New York City, that showed cold and dry weather types (DT and DP) to be associated with spikes in asthma hospitalisations (Lee et al., 2012). While we also observed an increased RR of asthma hospitalisation in the DT weather type in all the single pollutant models, it was insensitive to adjustment for aeroallergens; however, this weather type was also the least frequently experienced in Canada. For the DP weather type, RRs were consistently reduced in all the pollutant models except for PM_{10}, and in each case except PM_{10} were significantly reduced after adjustment for aeroallergens. Dry, cold, DP-type weather is typically associated with asthma exacerbation (D'Amato and Cecchi, 2008) and this weather type is the third most commonly experienced in Canada, with the highest overall rate of asthma admissions. Vanos et al. (2014) found significant modifications of the risk of cardiovascular and respiratory mortality, due to CO, NO_2, SO_2 and O_3, with the highest effect when DT and MT weather types were present. In the DM, MM and MT weather types, increases in mortality risk estimates due to pollutant exposure have been observed, as well as an additional greater likelihood of extreme pollutant events in DT weather (Vanos et al., 2013).

DT and MT are associated with high mortality due to the effects of heat (Sheridan et al., 2009); however, we found the effect of these two weather types on asthma hospitalisations to be less pronounced. The highest RR was for carbon monoxide in the MP weather type, and it was also one of the pollutant models most affected by adjustment for aeroallergens. There is some evidence that carbon monoxide is associated with asthma exacerbation (Peel et al., 2005), and our recent work comparing low and high air pollution also found significant increases in hospitalisations for CO with increases in the aeroallergens ascomycetes, basidiomycetes, and deuteromycetes equivalent to their pooled interquartile ranges (Cakmak et al., 2012).

There is consistent evidence that ozone is associated with asthma (Galan et al., 2003), that it interacts significantly with allergens, possibly by priming airways for inflammation (Kehrl et al., 1999), and that it can be modified by weather type (Hanna et al., 2011). The highest RR of asthma hospitalisation in the present study was found for ozone in the TR, transitional, weather type, as was also found by Hanna et al. (2011).

The RR of PM_{10} exposure on asthma hospitalisations was not significantly affected by adjustment for aeroallergens in any of the seven weather types. This is consistent with confounding of the results as fungal spores and pollen also fall within the particulate size range encompassed by PM_{10}. Additionally, while the PM_{10} model did find elevated RR, the effect size was lower than for any of the other pollutants. The effect of PM_{10} on asthma is not considered to be as great as that of $PM_{2.5}$. While one study in Canada found an effect of PM_{10} on asthma admissions and none for $PM_{2.5}$ (Lin et al., 2002), the greater effect of $PM_{2.5}$ is supported by laboratory studies. $PM_{2.5}$ has been shown to be more associated with oxidative stress in rat lung epithelial cells than PM_{10}, suggesting it may be more involved in asthma exacerbation (Choi et al., 2004). A number of human studies further support a role for $PM_{2.5}$ in the aetiology of asthma exacerbations (Anderson et al., 2013; Fann et al., 2012; Penttinen et al., 2006).

For NO_2 and SO_2, we found the highest RR occurred in the DM weather type, and in both cases this was significantly different after adjustment for aeroallergens. Both NO_2 and SO_2 have been found to increase hospital admissions for respiratory disease (Ren and Tong, 2008), and lab studies have found that exposure to NO_2 enhances asthmatic response to allergens (Strand et al., 1997). Our findings suggest an additional modifying effect for aeroallergens on the relationship between SO_2 and asthma hospitalisations.

4.1. *Study limitations*

Pooling the effect size estimates was necessary to obtain sufficient statistical power, but heterogeneity in the dataset, from using ten cities spaced across a wide geographical range, limits the applicability of these findings to individual cities. While we found regional similarities, the cities vary in pollution levels and types of vegetation and thus exposure to aeroallergens, and also in socioeconomic factors, which may affect how the population responds to environmental stress. Some of the weather types were relatively infrequent in Canada and the SSC approach is a relative, rather than absolute, classification. As a result, comparisons between synoptic weather types in Canada may not be readily comparable elsewhere. Insufficient numbers of observations for aeroallergens in some of the weather types likely contributed to the higher confidence intervals. This situation arises as the pollen season for trees, grasses, and weeds, peak at different times of the year and do not persist for as long as that of fungal spores, and pooling the aeroallergen counts, as was done here, limits exploration of these differences.

5. Conclusions

Synoptic weather types are known to modify levels of air pollution and aeroallergens. Here, we found that the dry polar, moist moderate, moist polar and transitional weather types present the highest relative risks of asthma hospitalisation in 10 Canadian cities, and the levels of risk were modified by adjustment for aeroallergens. Synoptic forecasting may help prepare for and mitigate spikes in asthma admission rates, particularly when used in combination with information on airborne allergens, and decreasing air pollutant levels should lower the risk of asthma exacerbations and hospitalisations due to aeroallergens.

Competing financial interests declaration

All authors have no competing financial interests.

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