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Lisa Buettner Mohr ^a; Suhong Luo ^a; Erin Mathias ^a; Ratna Tobing ^a; Sharon Homan ^a; David Sterling ^a

^a School of Public Health, St. Louis University, St. Louis, MO, United States

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ORIGINAL ARTICLE

Influence of Season and Temperature on the Relationship of Elemental Carbon Air Pollution to Pediatric Asthma Emergency Room Visits

LISA BUETTNER MOHR, SUHONG LUO, ERIN MATHIAS, RATNA TOBING, SHARON HOMAN, AND DAVID STERLING

St. Louis University, School of Public Health, St. Louis, MO 63104 United States

Previous studies have demonstrated an association between air pollution and asthma exacerbation. Less understood is the effect of elemental carbon (EC), and the interaction of EC with temperature, on increases in pediatric asthma emergency department visits and how these relationships change across the seasons in a metropolitan area with several industries and relatively low air pollution. Measurements of EC, ozone (O₃), sulfur dioxide (SO₂), and total oxides of nitrogen (NO_x) were available from the St. Louis EPA Supersite for June 1, 2001 to May 31, 2003. We obtained ICD-9 information on 281,763 pediatric ED visits from 27 hospitals in the St. Louis, MO metropolitan area. The relationship between EC and pediatric asthma ED visits, controlling for season, weekend exposure, allergens, and other pollutants known to exacerbate asthma, was assessed using Poisson generalized estimating equations using a 1-day lag between exposure and ED visit. We evaluated the interaction of EC and temperature and EC and weekend vs. weekday exposure. An interaction effect existed between EC and temperature for 11–17-year-olds during the summer and winter seasons. During the summer, a 0.10 µg/m³ increase in EC resulted in a 9.45% increase in asthma ED visits among 11–17-year-olds (95%CI = 1.02,1.17) at the median seasonal temperature (86.5°F). This risk increased with increasing temperature. During the winter, a 0.10 µg/m³ increase in EC resulted in 2.80% increase in asthma ED visits among 11–17-year-olds (95%CI = 1.01,1.05) at the median seasonal temperature (43.3°F). This risk increased with decreasing temperature. Among 11–17-year-olds, daily number of asthma ED visits is associated with increased levels of EC at higher temperatures in the summer and lower temperatures in the winter.

Keywords asthma, children, air pollution, elemental carbon, temperature

BACKGROUND

Asthma is the most common chronic childhood illness affecting an estimated 9 million children under the age of 18 in the United States, accounting for more pediatric hospital admissions and emergency department (ED) visits than any other childhood disease (1). The prevalence of asthma in the U.S. has increased by more than 75% since 1980 (2).

In 2002, children under the age of 18 had over 727,000 ED visits, a rate of 100 per 10,000 children. The ED visit rate was highest among children aged 0–4 years at 162 per 10,000 children (3). Among children ages 5 to 17, asthma is the leading cause of school absences from a chronic illness (4), accounting for an annual loss of more than 14 million school days per year (approximately 8 days for each student with asthma) (2, 5).

Asthma severity varies by age of onset and seasonal stimuli. Previous panel studies of asthma in children have shown that seasons are significantly related to asthma worsening with the greatest number of exacerbations occurring in autumn and the fewest in the midsummer (6–13). Increase in long-term exposure to background ambient air pollution is associated with an increased prevalence of respiratory and atopic indicators in children. Penard-Morand et al. report that after adjusting for confounders, asthma was associated with an increase in the exposure to sulfur dioxide (SO₂), particulate matter with

an aerodynamic diameter of less than 10 or 2.5 micrometers (PM₁₀ or PM_{2.5}), and ozone (O₃) (14).

Children with asthma are particularly at risk for adverse health effects related to pollutant exposure because of the rapid development of the respiratory system in the early years of life. Elemental carbon (EC) is one component of PM_{2.5} that has recently been associated with respiratory health effects in children (15). Previous studies have shown that exposure to ambient air pollutants such as nitrogen dioxide (NO₂), acid vapor, PM₁₀, PM_{2.5}, O₃ and EC during the early years of life is linked to increases in respiratory symptoms, emergency visits, and significant decreases in lung function measurements as children reach adulthood (16–25).

The purpose of this study is to determine whether the number of pediatric asthma ED visits in the St. Louis, MO metropolitan area, which ranked 6th in asthma morbidity out of 100 U.S. metropolitan areas in 2005, is associated with the level of EC particulate matter (aerodynamic diameter ≤ 2.5 µm) during any of the seasons (26). St. Louis is a relatively low pollution city, with the exception of ozone; therefore, this study will look at the effect of the elemental carbon component of fine particles at levels below the EPA Air Quality standard for fine particles. Further, we suspect that temperature modifies the effect of EC after adjusting for the confounding effects of other air pollutants known to exacerbate asthma including total oxides of nitrogen (NO_x), SO₂ and O₃.

METHODS

Study Population

The study population consisted of children aged 2–17 years admitted for emergency care for asthma at any St. Louis, MO area hospital between June 1, 2001 and May 31, 2003.

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Corresponding author: Lisa Buettner Mohr, St. Louis University, School of Public Health, 3545 Lafayette Ave., St. Louis, MO 63104 United States; E-mail: lbuett1@slu.edu

Children under the age of 2 years were excluded from the study because of the difficulty of correctly diagnosing asthma. The National Asthma Education and Prevention Program Coordinating Committee recommends the use of medical history to diagnosis asthma in children under 5 years of age, and the medical history of infants and toddlers under the age of 2 may not contain enough information to make a reasonably reliable diagnosis (27). Through a data use agreement with the Missouri Hospital Association, the Hospital Industry Data Institute (HIDI) provided data on all ED visits to the hospitals in this region. Two of the 27 hospitals reporting pediatric asthma ED visits were major research hospitals and 2 were children's hospitals. The Primary International Classification of Disease, Ninth Revision, (ICD-9) diagnosis code of 493 with any fourth and fifth digit extension was used to identify visits where asthma was the primary diagnosis. Eligibility was restricted to patients residing in one of 175 zip code areas that are at least partially or completely part of the St. Louis metropolitan area, which comprised an area of 1,527.5 square kilometers. Repeat asthma visits on a single day were counted only once.

The Institutional Review Board of Saint Louis University approved the study protocol.

Air Quality Data and Temperature

Air quality indices used in this study include O_3 , elemental carbon particulate matter less than or equal to $2.5 \mu m$ in diameter (EC), NO_x , SO_2 , and maximum daily temperature. Air quality and temperature data for the study period were obtained from the US EPA funded St. Louis Midwest Supersite, a single monitoring station located in a relatively low density, mixed use (residential/light commercial) neighborhood approximately 3 kilometers east of the City of St. Louis, MO central business district and operated by the Air Quality Laboratory at Washington University. The Supersite regularly collected samples to measure over 50 ambient air pollutants, 7 days a week, on continuous, hourly, daily, and monthly schedules depending on the pollutant and air monitoring methods. The air sample collection methods used at the Supersite have been described in detail elsewhere (28).

Aeroallergens

Aeroallergens used in this study include tree, weed, and grass pollen and total mold spore count. The pollen counts were categorized as absent, low, and moderate-to-high, and the mold counts were categorized as low, moderate, and high based on the National Allergy Bureau scale (29). Aeroallergen data for the study period were obtained from the St. Louis County Health Department, which has been collecting such information since 1960. The St. Louis County Health Department collected Burkard spore trap samples every 24 hours, except on weekends and holidays. The authors imputed missing daily counts using data from the closest available day.

Statistical Analysis

The averaging times for all pollutants followed federal standards: EC, 24-hour average; O_3 , 8-hour average; SO_2 , 1-hour maximum; NO_x , 1-hour maximum. For each air pollutant, we applied a 1-day measurement lag. This decision was based on the results of similar studies and information

provided by local pediatric asthma specialists (29, 30). Relative risks were calculated using a one standard deviation increase in EC to facilitate comparability across studies. The maximum daily temperature was also selected for inclusion in the analysis. Missing pollutant or temperature data resulted in the exclusion of 39 days from the analysis out of a possible 730 days.

Strong seasonal variation exists with respect to the daily number pediatric ED visits as well as pollutant levels, including mold and pollen counts. To control for these factors we chose four 3-month seasons that reflected seasonal characteristics (i.e., temperature and pollutant fluctuation, school year). Separate models were fit as described below for each season: winter (December, January, and February), spring (March, April, and May), summer (June, July, and August), and fall (September, October, and November). We observed that Sunday and Monday had, on average, higher counts of pediatric asthma ED visits than the other days of the week (16.6 vs 13.4 visits). Using our a priori assumption of a 1-day lag for air pollutant measures, this translated to a Saturday and Sunday (i.e., weekend) exposure. In addition to a weekend/weekday pattern in asthma ED visits, previous studies indicated differences between weekend and weekday concentrations of atmospheric pollutants (31–33). Therefore, we included a weekend/weekday indicator variable in the model.

A Poisson regression model with a log link function was fitted for each season using generalized estimating equation (GEE) analysis. All statistical modeling was performed with the GENMOD procedure in SAS 9.1 (34). The natural log of the expected number of pediatric asthma emergency department visits on day t was modeled as

$$\begin{aligned} \ln [\text{ED visits}_t] = & \beta_0 + \beta_1 \text{EC}_{t-1} + \beta_2 O_{3\ t-1} + \beta_3 \text{NO}_{x\ t-1} \\ & + \beta_4 \text{SO}_{2\ t-1} + \beta_5 \text{MaxTemp}_t \\ & + \beta_6 \text{WeekendExp} + \beta_7 \text{Mold}_{\text{High}} \\ & + \beta_8 \text{Mold}_{\text{Mod}} + \beta_9 \text{Tree}_{\text{Mod/High}} + \beta_{10} \text{Tree}_{\text{Low}} \\ & + \beta_{11} \text{Weed}_{\text{Mod/High}} + \beta_{12} \text{Weed}_{\text{Low}} \\ & + \beta_{13} \text{Grass}_{\text{Mod/High}} + \beta_{14} \text{Grass}_{\text{Low}} \\ & + \beta_{15} \text{EC}_{t-1} \text{MaxTemp}_t + \beta_{16} \text{EC}_{t-1} \text{WeekendExp} \end{aligned}$$

where WeekendExp was an indicator variable for weekend air pollution exposure, with weekdays (Monday through Friday) as the reference level. Air pollutants and the maximum daily temperature were treated as continuous variables for all analyses. For each season, we estimated the adjusted relative risk (RR) and 95% confidence interval for EC. The best model for each season was determined by first evaluating the need to include interaction terms for EC and other air quality measures (i.e., $\beta_7 \text{EC}_{t-1} \text{MaxTemp}_t$), followed by a determination of which potentially confounding air quality variables should be retained in the model. Confounding variables were eliminated only when the adjusted EC rate ratio remained unchanged and the confidence interval narrowed.

Seasonal models were fit for the entire study period as well as separate seasonal models for each year of data, resulting in a total of three models per season.

TABLE 1.—Demographic information and temporal variation in pediatric emergency department visits in the St. Louis, MO metropolitan area (June 1, 2001–May 31, 2003).

	Asthma Visits (n = 13,344)		Non-Asthma Visits (n = 268,419)	
	No.	%	No.	%
Age (in years)				
2–5	4,765	35.7	79,083	29.4
6–10	4,376	32.8	71,036	26.5
11–17	4,203	31.5	118,300	44.1
Gender				
Male	7,927	59.4	139,815	52.1
Race				
White	3,915	29.3	153,725	57.3
Black	9,153	68.6	104,971	39.1
Other	276	2.1	9,723	3.6
Weekday				
Sunday	2,211	16.6	41,034	15.3
Monday	2,245	16.8	39,868	14.9
Tuesday	1,979	14.8	38,842	14.5
Wednesday	1,876	14.1	37,738	14.1
Thursday	1,676	12.6	37,376	13.9
Friday	1,675	12.6	35,215	13.1
Saturday	1,682	12.6	38,345	14.3
Season				
Summer	1,875	14.1	63,491	23.7
Fall	4,544	34.1	66,532	24.8
Winter	3,082	23.1	66,109	24.6
Spring	3,843	28.8	72,287	26.9

RESULTS

A total of 281,763 pediatric ED visits occurred at the 27 hospitals in the St. Louis, MO metropolitan area between June 1, 2001 and May 31, 2003; 12,836 (4.6%) of the visits were for asthma. The average number of daily ED visits was 386 (standard deviation, 52), while the average number of daily ED visits for asthma was 18 (standard deviation, 9; range 3–50). The distributions of various demographic and temporal characteristics by asthma status are presented in Table 1.

Relative to the non-asthma cases, the asthma cases had a higher proportion of males as well as a higher proportion of African Americans. The number of ED visits for asthma showed variation across weekdays, with Sunday and Monday being high ED use days. The number of asthma ED visits also showed variation across seasons, which was not observed among the non-asthma cases.

During the study period, both O_3 and $PM_{2.5}$ exceeded the U.S. Environmental Protection Agency's National Ambient Air Quality Standards. Ozone exceeded the national standard 18 times while $PM_{2.5}$ exceeded the national standard 3 times. The ozone exceedance days occurred from June through September while the $PM_{2.5}$ exceedance days occurred on July 4th and/or 5th. Descriptive statistics for air quality data are presented in Figure 1.

Table 2 contains Pearson correlation coefficients among air quality variables and maximum daily temperature. Nitrous oxides were significantly correlated with EC, and ozone was significantly correlated with maximum daily temperature.

We compared the parameter estimates and adjusted EC relative risks for each set of seasonal models. The data are not shown for the analyses of the seasonal models for each year of the study. The resulting model coefficients varied for the winter, spring, and summer models; however, the adjusted EC RRs were essentially the same. For the fall models,

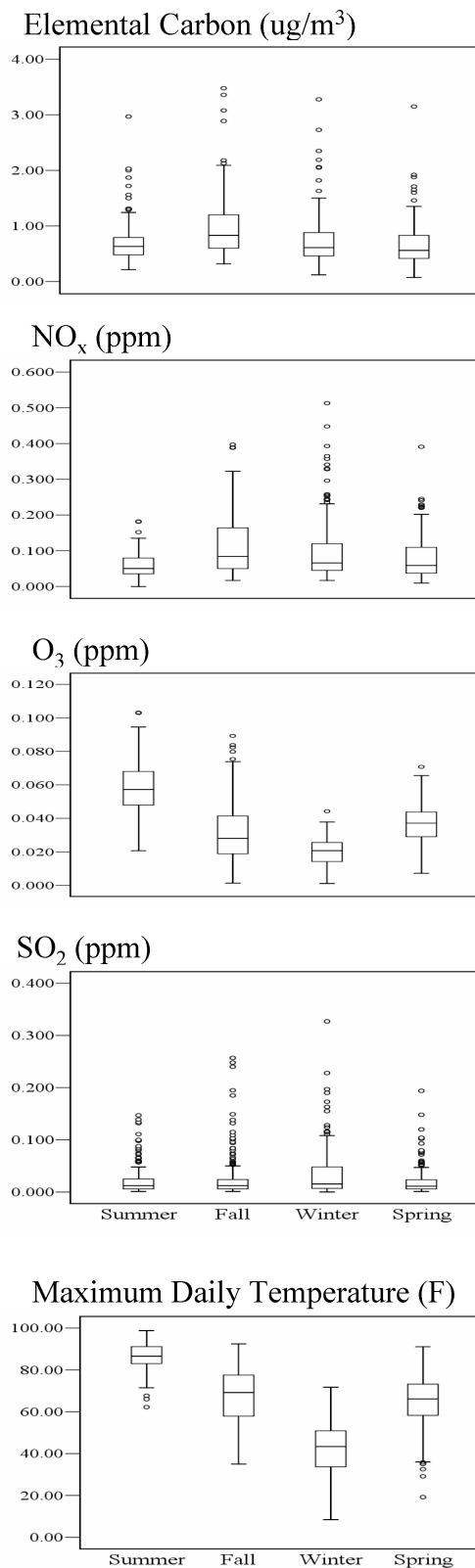


FIGURE 1.—Seasonal variation of EC, NO_x , O_3 , SO_2 , and maximum daily temperature box plots in the St. Louis, MO metropolitan area (June 1, 2001–May 31, 2003).

TABLE 2.—Pearson correlation coefficients for maximum daily temperature and air pollutants.

	PM _{2.5} EC ($\mu\text{g}/\text{m}^3$)	NO _x (ppm)	SO ₂ (ppm)	O ₃ (ppm)
PM _{2.5} EC ($\mu\text{g}/\text{m}^3$)	1.00			
NO _x (ppm)	0.68*	1.00		
SO ₂ (ppm)	0.09	0.10	1.00	
O ₃ (ppm)	-0.06	-0.17	-0.06	1.00
Maximum Temperature (F)	0.02	-0.15	0.03	0.75*

*Indicates statistical significance at the $p = 0.05$ level.

neither the coefficients nor the adjusted EC RRs varied. The slight variation in coefficients and adjusted rate ratios indicated that it is not necessary to present results from each of the three models generated for each season; only results from seasonal models for the entire study period are discussed in this paper.

Table 3 presents the adjusted RRs and 95% confidence intervals for weekend and weekday exposure by age group for a 0.10 microgram/ m^3 increase in EC at the median seasonal temperature for each seasonal Poisson regression model. The adjusted RR and confidence interval for EC during the fall for 2–5-year-olds with weekend exposure is 1.03 (95% CI: 1.01, 1.05). Therefore, during the fall, there was a 3.00% (1.00% to 5.00%) average increase in asthma ED visits among 2–5-year-olds with weekend exposure per 0.1 $\mu\text{g}/\text{m}^3$ increase in EC. Among 11–17-year-olds, during the summer, the adjusted RR for a 0.1 $\mu\text{g}/\text{m}^3$ increase in EC was 1.09 for weekend exposures (95% CI: 1.02, 1.17), and during the winter, the adjusted RR was 1.03 for weekday exposures (95% CI: 1.00, 1.05). There was a reduced risk for asthma ED visits associated with a 0.1 $\mu\text{g}/\text{m}^3$ increase in EC for weekend exposure in the 2–5-year-old age group and in all ages in the spring and in the 6–10-year-old age group in the fall.

The interaction of EC and temperature was statistically significant for the fall, winter, and summer seasons. Because of the interaction of temperature and EC, we estimated the

TABLE 3.—Relative risk for a 0.1 $\mu\text{g}/\text{m}^3$ increase in EC from separate Poisson regression models for each season by weekday exposure (at median seasonal temperature).

Season	Weekend Exposure		Weekday Exposure	
	Relative Risk	95% CI	Relative Risk	95% CI
2–5-year-olds				
Summer	1.01	(0.93, 1.09)	0.97	(0.94, 1.01)
Fall	1.03	(1.01, 1.05)	1.00	(0.99, 1.02)
Winter	1.00	(0.96, 1.05)	1.02	(0.99, 1.04)
Spring	0.92	(0.86, 0.98)	0.99	(0.95, 1.03)
6–10-year-olds				
Summer	0.98	(0.77, 1.26)	1.02	(0.98, 1.05)
Fall	0.97	(0.95, 1.00)	0.99	(0.97, 1.01)
Winter	1.00	(0.96, 1.05)	1.03	(1.00, 1.05)
Spring	0.96	(0.90, 1.02)	0.98	(0.95, 1.01)
11–17-year-olds				
Summer	1.09	(1.02, 1.17)	1.01	(0.98, 1.04)
Fall	0.97	(0.94, 1.00)	1.00	(0.97, 1.02)
Winter	1.01	(0.97, 1.06)	1.03	(1.00, 1.05)
Spring	0.99	(0.94, 1.05)	0.99	(0.96, 1.03)
All ages				
Summer	1.05	(1.00, 1.11)	1.01	(0.98, 1.03)
Fall	0.99	(0.97, 1.01)	1.00	(0.99, 1.01)
Winter	0.96	(0.92, 1.00)	0.99	(0.96, 1.01)
Spring	0.96	(0.92, 1.00)	0.98	(0.96, 1.01)

*EC exposure increment is equal to one standard deviation.

adjusted rate ratio for a one standard deviation increase in EC at the 10th, 25th, 50th, 75th, 90th percentiles of the maximum daily temperature for each season. The estimated RRs and 95% confidence intervals are graphed in Figure 2.

The interaction of EC and temperature is clearly evident for the fall, winter, and spring seasons. During the summer and fall the adjusted RR increases with temperature while the inverse is true during the winter and spring. The interaction of weekday vs. weekend exposure with EC and temperature is also evident, particularly in the 11–17-year-olds during the summer and winter seasons. For this group, the combination of weekend exposure, increasing temperature, and a 0.1 $\mu\text{g}/\text{m}^3$ increase in EC results in increasing risk during the summer; and the combination of weekday exposure, decreasing temperature, and a 0.1 $\mu\text{g}/\text{m}^3$ increase in EC results in increasing risk during the winter.

The adjusted RR and confidence intervals for NO_x, O₃, and SO₂ are reported in Table 4. In the spring, a 10 ppb increase in NO_x increased daily pediatric asthma ED visits by an estimated 4% among 2–5-year-olds (RR: 1.04, 95% CI: 1.01, 1.09) and by an estimated 5% among all ages (RR: 1.05, 95% CI: 1.01, 1.09). A 10 ppb increase in NO_x also significantly increased asthma ED visits among 6–10-year-olds in the fall (RR: 1.07, 95% CI: 1.04, 1.15). There was also a marginally significant increase in asthma ED visits among 11–17-year-olds and all ages after a 10 ppb increase in NO_x during the fall season. A 10 ppb increase in O₃ was related to a 7% increase in asthma ED visits among all ages in the spring (RR: 1.07, 95% CI: 1.01, 1.14). Significant changes in pediatric asthma ED visit rates were not associated with SO₂ during any of the seasons for any of the age groups.

DISCUSSION

Elemental carbon consists of respirable size black solid particles of soot, most of which have aerodynamic diameter of less than 2.5 micrometers. This small size allows the pollutant to reach the alveoli regions of the lungs, where it may be deposited with the greatest potential adverse health effects, including asthma worsening. The St. Louis Midwest Supersite collected elemental carbon with the possibility of using EC as a surrogate for diesel particulate matter. The terms elemental carbon (EC), black carbon (BC) and “soot” are often used by atmospheric researchers to designate products of incomplete combustion that contain randomly oriented graphitic structures interspersed with other compounds. Other combustion processes such as fireplaces, forest fires, gasoline engines, agricultural burning, and power plants also emit EC.

This study provides evidence of an ecological association between the daily number of pediatric asthma ED visits and the level of EC PM_{2.5} in the fall season for 2–5-year-olds and in the winter and summer seasons for 11–17-year-olds. Further, we found that daily maximum temperature modified the effect of EC after adjusting for the confounding effects of other air pollutants known to exacerbate asthma including SO₂, NO_x and O₃. As illustrated in Figure 2, for the fall season for 2–5-year-olds, the adjusted rate ratio for ED visits associated with EC increased as the daily maximum temperature increased. At the median daily maximum temperature for fall, the estimated relative risk for a 0.10 $\mu\text{g}/\text{m}^3$ increase

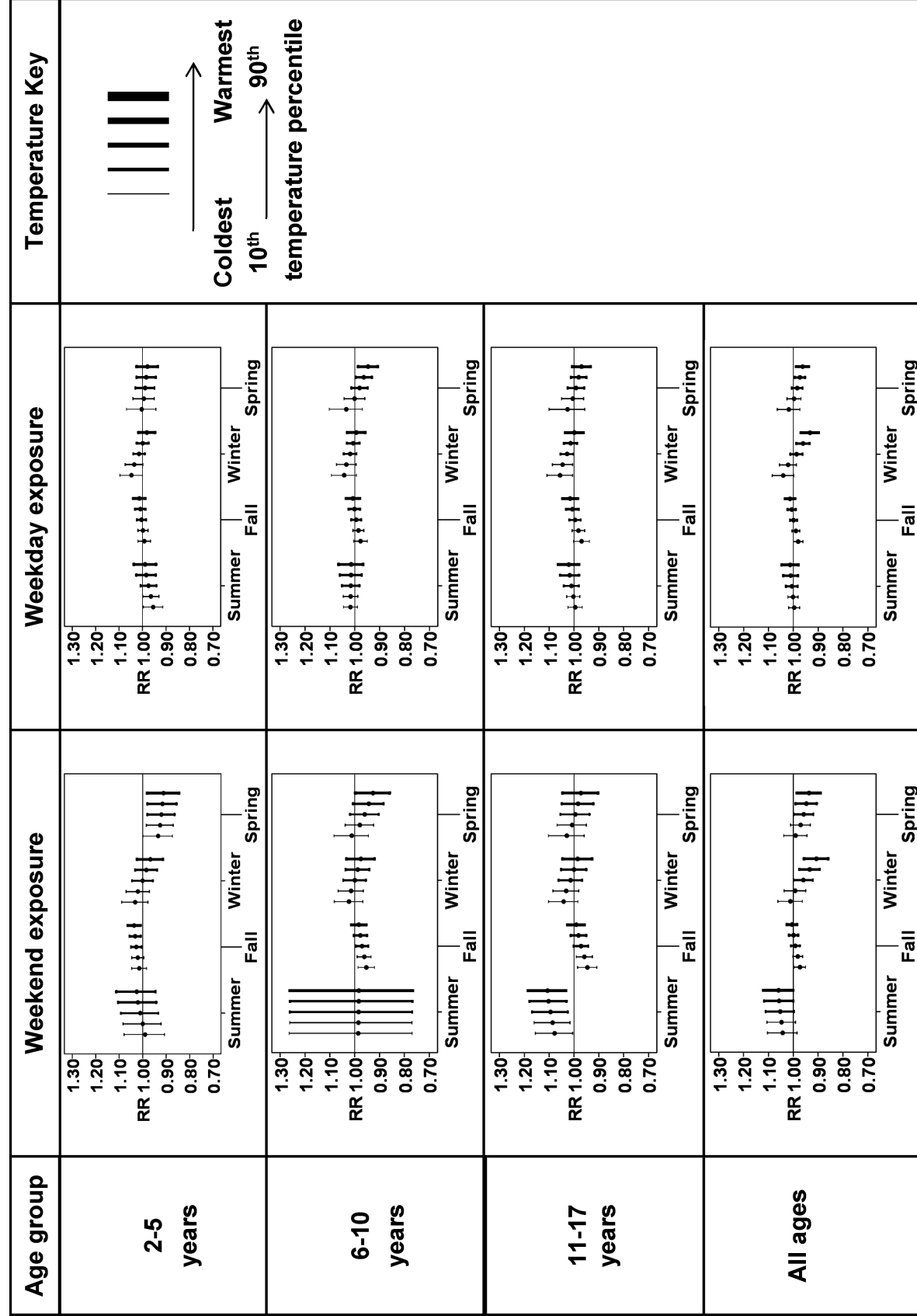


FIGURE 2.—Relative risk (RR) for pediatric asthma ED visits associated with EC air pollution at varying temperatures, stratified by age group and weekend vs. weekday exposure. *Note:* Bars represent the 95% confidence interval for the estimated RR based on a 0.10 microgram/m³ increase in EC.

TABLE 4.—Relative risks and 95% confidence intervals from separate Poisson regression models for each season by age group examining a 10 ppb* increase in pollutant concentration.

Pollutant	Season	Age groups							
		2–5 years		6–10 years		11–17 years		All ages	
		RR*	95% CI*	RR*	95% CI*	RR*	95% CI*	RR*	95% CI*
NO _x	Spring	1.04	1.01, 1.09	1.03	0.93, 1.14	1.09	0.99, 1.21	1.05	1.01, 1.09
	Summer	1.03	0.99, 1.21	1.06	0.96, 1.18	1.00	0.92, 1.10	1.05	0.98, 1.13
	Fall	0.96	0.87, 1.06	1.07	1.04, 1.15	1.09	1.00, 1.16	1.03	1.00, 1.16
	Winter	0.97	0.87, 1.08	0.98	0.87, 1.09	0.92	0.82, 1.04	0.98	0.89, 1.19
SO ₂	Spring	0.99	0.93, 1.06	0.99	0.92, 1.07	0.98	0.91, 1.07	0.99	0.94, 1.05
	Summer	1.00	0.92, 1.09	0.96	0.87, 1.07	1.05	0.97, 1.14	0.99	0.93, 1.05
	Fall	1.05	0.97, 1.13	1.01	0.93, 1.09	0.94	0.85, 1.03	1.01	0.95, 1.06
	Winter	1.03	0.95, 1.11	1.01	0.93, 1.09	0.99	0.91, 1.08	1.03	0.96, 1.10
O ₃	Spring	1.03	0.96, 1.12	1.09	0.99, 1.19	1.07	0.98, 1.18	1.07	1.01, 1.14
	Summer	0.96	0.88, 1.06	1.00	0.88, 1.09	0.90	0.82, 0.98	0.96	0.90, 1.03
	Fall	0.97	0.89, 1.06	0.99	0.91, 1.08	1.08	0.97, 1.19	1.01	0.95, 1.07
	Winter	0.92	0.85, 1.01	0.94	0.86, 1.03	0.96	0.87, 1.05	1.05	0.97, 1.14

*NO_x, total oxides of nitrogen; SO₂, sulfur dioxide; O₃, ozone; RR, relative risk; CI, confidence interval; ppb, parts per billion.

in the elemental carbon level for 2–5-year-olds is 1.03 (95% CI: 1.01, 1.05). This study also found that the estimated relative risk for asthma ED visits among 11–17-year-olds increased as temperature increased during the summer season when exposure occurred on a weekend and as temperature decreased during the winter season when exposure occurred on a weekday. Previous studies have reported that pediatric asthma morbidity is seasonal, with the fewest exacerbations in the summer and the most in the fall, particularly with the opening of school (7). Greater outdoor exposure may also occur during fall, particularly when the temperature is warm, and on weekends when children have time to play outside or participate in outdoor sports.

As Silverman and colleagues note, there are a number of possible explanations for the increased asthma morbidity at the start of school, including emotional factors, stress, and viruses. In St. Louis, the highest number of asthma ED visits occurs in the fall (see Table 1) (7). From 1990 to 2005, peak submission of respiratory specimens at the Virology Laboratory of Cardinal Glennon Children's Hospital, which serves several hospitals in the St. Louis metropolitan area, occurred in the winter from December to February (35). Therefore, the peak in daily asthma ED visits in the fall is not a result of respiratory viruses; however, it is possible that this contributed to the increase in asthma ED visits during the winter season. Figure 2 clearly shows that during the fall the rate of pediatric asthma ED visits among 2–5-year-olds increases as the temperature increases, which would be associated with greater likelihood of children playing outdoors. Notice that the winter adjusted rate ratio estimates for EC increase as temperature decreases. It is likely that the additional stress of cold air combined with EC exacerbates asthma problems, increasing the likelihood of ED visits. In the 11–17-year-old age group, this relationship is highly significant for weekday exposure. This may reflect extra time spent outside waiting for the school bus, walking to school, or driving or riding to school in a car that has yet to heat up. The summer adjusted RR estimates for EC also increase, but as temperature increases. In the 11–17-year-old age group, this relationship is particularly important for weekend exposure. This age group, having more autonomy than younger children, may be more likely to spend time outside on weekends with friends and

family regardless of the temperature. In this situation, it may be that relationship is due to a combination of high temperatures and the high relative humidity that accompanies high temperatures in the Midwest. Unfortunately, the authors did not have access to measures of relative humidity during this time period. The 11–17-year-old age group represents a unique group of individuals who are likely to have long-term asthma management plans in place and to have their asthma under control. Based on this, the authors assume that asthma exacerbation leading to an ED visit in this age group is a result of the individuals' time-activity patterns leading to increased exposure to ambient outdoor air.

This study also found season/temperature periods that resulted in a reduced risk for pediatric asthma ED visits, most notably in the spring for the 2–5-year-old age group and all ages, and in the fall for the 6–10-year-old age group. It is likely that this reduced risk is related more to time-activity patterns than the EC concentrations in the air. That is, time spent outside is directly related to both temperature and season, as well as precipitation, which was not included in this study.

Bae and colleagues reported that for the year of 2002, St. Louis EC concentrations showed weekly and daily patterns, with EC concentrations peaking during morning rush hour traffic during the week. This may partially explain the higher numbers of asthma ED visits during the school seasons (fall, winter, and spring) than the summer, because children are more likely to be exposed to rush hour traffic, while waiting for and riding in school buses and walking to school (31). Sabin et al. reported EC levels between 0.9 and 19 $\mu\text{g}/\text{m}^3$ in diesel school buses and vehicles following diesel school buses (36). These EC levels are more than 5 times greater than the maximum and nearly 25 times greater than the average levels reported at the St. Louis Supersite.

Tolbert and colleagues fit Poisson models with a log link function using GEE analysis to study pediatric ED visits in the Atlanta metropolitan area during the summers of 1993–1995 (29). Using a one-day lag for each air quality variable, adjusting for temperature, day of the week and year, they estimated the rate ratio for PM₁₀ to be 1.04. Temperature was not significant; however, the authors did not evaluate temperature-pollutant interactions. As seen in Figure 2, we also found the

temperature-EC interaction to be insignificant in the summer season, except for 11–17-year-olds. In the summer, the adjusted rate ratio for EC increased as temperature increased. As seen in the temperature boxplot (Figure 1), summer temperatures in St. Louis were very high. Young children likely spent much more time indoors in the air conditioning when the temperature is in the 90°F range than when temperature drops to the 80°F range. We suspect that EC levels in the summer were not statistically related to the number of daily asthma ED visits among 2–5-year-olds and 6–11-year-olds because of limited outdoor exposure on hot days.

Previous studies of pediatric asthma have examined the effect of allergens on ED visits and found significant associations between the number of asthma ED visits and the daily pollen count (37). However, it is important to note that Lierl and Hornung did not include daily temperature or EC in their analyses. In this study, pollen and mold were treated strictly as confounders, as the focus of this study was on the importance of EC in pediatric asthma exacerbation. However, the analysis indicated that allergens may play an important role in asthma exacerbation across age groups, particularly during the spring season.

The interpretation of the evidence of a statistical association between ambient air pollution levels and pediatric asthma ED visits was contingent on four features of the study design. First, the monitoring station was located east of the St. Louis, MO metropolitan area, and it was assumed that the ambient air quality measures were representative of the entire study area. Second, it was assumed that ambient air pollutant levels were meaningfully related to personal exposure. Third, only patients whose zip code of residence was in the St. Louis, MO metropolitan area were included in the study, which assumed that the patient was in the study area the previous day. Fourth, the study design was retrospective, so it was not possible to obtain information not present in the data provided by HIDi.

Study strengths included rigorous air pollution measurement, a larger number of pediatric asthma ED visits compared to most previous studies, a strong epidemiological modeling strategy, and complete ED visit data due to the mandatory reporting of all emergency department visit data to HIDi by all Missouri hospitals.

Future research is needed to determine how relative humidity effects the interaction between EC and temperature during the summer season and how this then influences pediatric asthma ED visits. Further research should also focus on the specific contributions of allergens to the relationship between air pollution and asthma exacerbation.

This study showed that, particularly among 11–17-year-olds, an increase in EC coupled with an increase in temperature during the summer or a decrease in temperature during the winter may increase the risk for severe asthma exacerbation resulting in an ED visit, and that this increased risk for asthma exacerbation may occur, even at pollutant levels below the EPA's National Ambient Air Quality Standards.

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