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Health Services Utilization in Asthma Exacerbations and PM_{10} Levels in Rural Colorado

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Abstract

Rationale: The San Luis Valley in rural Colorado often has elevated levels of ambient particulate matter. To date little is known about the impact of ambient particulate matter levels and medical care utilization due to asthma exacerbation in rural communities.

Objectives: We investigated the impact of ambient particulate matter concentrations on emergent/urgent visits and hospitalizations for asthma in a rural community.

Methods: Daily ambient particulate matter concentrations from an air quality monitor in the San Luis Valley (2003-2012) were obtained from the state health department. De-identified data for emergent/ urgent visits with a diagnosis code for asthma were collected from the local health care system organization. A generalized linear model using splines and employing generalized estimating equations for correlated measures over time was used to examine the association between daily counts of emergent/ urgent visits for asthma and 3- to 5-day averaged ambient particulate matter concentrations.

Results: For each 15 $\mu g/m^3$ increase in 3-day averaged ambient particulate matter, there was an associated 3.1% increase in hospital counts for all asthma patients (95% CI: 0.3 to 5.9%; p=0.03). When the 3-day average exceeded 50 $\mu g/m^3$, asthma hospital visits increased by 16.8% (p=0.03), and when it exceeded 100 $\mu g/m^3$, visits increased by 65.8% (p=0.002). In children, the odds of one asthma event requiring an emergent/urgent care visit increased 5.0% with each 15 $\mu g/m^3$ increase in 3-day averaged ambient particulate matter (p=0.22).

Conclusion: We observed associations between ambient air PM_{10} levels and emergent/urgent care visits and hospitalization counts in a rural U.S. community prone to dust storms and Environmental Protection Agency exceedances.

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Particulate matter with a diameter less than 10 micrometers (μm) (PM_{10}) is a heterogeneous mixture composed of hydrocarbons, transition metals, and endotoxins (1). In rural areas, 80% of PM_{10} is composed of windborne crustal elements, whereas in urban areas it primarily consists of automobile pollution and products of combustion (2).

Long-term exposure to particulate matter air pollution has been associated with premature mortality in those affected by respiratory and cardiovascular diseases (3, 4). Elevated PM_{10} levels are associated with exacerbations of respiratory conditions including COPD and bronchitis (5, 6), and are recognized to worsen asthma symptoms (5, 7, 8, 9). Among people with asthma experiencing higher exposure to PM_{10}, studies have found increased physician consultations for worsening asthma (10), greater use of asthma reliever medications, increased emergency room visits for asthma exacerbations (5, 7, 8, 9), and increased asthma-related hospitalizations with the association strongest in infants (11). Childhood asthma prevalence in the rural community observed in this study, the San Luis Valley (SLV), is 14% (12, 13) which is higher than the United States average of 12% (8) and it is therefore of public health importance to identify potential sources of asthma exacerbations in this community. In addition, PM_{10} levels in rural areas, similar to the SLV, have more frequent days where levels exceed the Environmental Protection Agency (EPA) maximum contaminant level (MCL) of 150 $\mu g/m^3$ (14).

Research has shown that asthma admissions rates are more associated with PM_{10} levels than fine particles (16). Studies have reported an increased risk for medical visits for asthma exacerbations of 3% to 6% for every 10 $\mu g/m^3$ increase in PM_{10} (16, 17). PM_{10} has been identified as an environmental trigger for asthma but in limited studies conducted in

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populations residing in urban areas and over short periods of time (7, 8, 11, 18). A review by Tzivian (8) calls for rigorous studies over longer periods of time and expanding to include rural and minority populations, this study addresses these identified limitations. Our current research is one of the first to examine the association between outdoor PM_{10} levels and EUH visits related to asthma exacerbation over a ten-year period in a rural, biethnic, underserved community.

Methods

Study Population

The SLV is a high-altitude (~7500 feet) rural community located in south central Colorado covering approximately 8000 square miles. It has a biethnic population of about 48,000 that is both white and Hispanic/Latino. The median income is approximately $29,650 with 25% living below poverty (19). The primary economic components are tourism and agriculture (ranching and potato crops) (19). The SLV is an arid climate with an average PM_{10} level of 25 $\mu g/m^3$ and a range of 6 to 484 $\mu g/m^3$ between 2001-2011 (20). On average the SLV has two times the number of average daily PM_{10} levels that exceed the EPA MCL of 150 $\mu g/m^3$ (14) than other areas of Colorado, including mountain, industrial, and urban areas (20).

Study Sample

We obtained data for all respiratory-related emergent/urgent visit and hospitalization (EUH visits) records from the regional medical center serving all of the SLV population (See

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Supplementary Material) for the years 2003 through 2012. We requested visit records limited to those with *International Classification of Diseases version 9* (ICD9) codes for asthma (493.x), pneumonia (481, 485, 486), acute respiratory illness (460.x, 462.x), and chronic obstructive pulmonary disease with bronchitis (490.x). Each record included patient age at the time of the visit, ICD9 code, and visit date. Patient sex was not included in the dataset because past research has not indicated that sex modifies the association between PM_{10} levels and asthma exacerbation (15). This study was approved with waiver of consent by the Colorado Multiple Institutional Review Board for human research.

Meteorological Data

The National Oceanic Atmospheric Association's (NOAA) publicly available meteorological data for 2003 to 2012 were obtained from the one meteorological station in the community, located at the regional airport, two miles south of the two monitors in Alamosa. Data included daily average temperature, daily total precipitation, daily average barometric pressure, and daily average wind speed. These variables were selected because of the strong association with elevated PM_{10} levels in ambient air (21). Each meteorological variable was incorporated into the statistical analysis in the original form (daily average or daily total).

Daily PM_{10} Levels

In the SLV, there are two ambient air monitoring stations, one at Adams State University and the second at a municipal building, located two miles apart in the city of Alamosa, which is where the largest portion of the population resides. Monitors are maintained by the Colorado

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Air Pollution Control Division (CAPCD) of the Colorado Department of Public Health and Environment (CDPHE) (35). PM_{10} levels were measured daily throughout the 10-year study period (2003-2012) from high-volume canister samples that use quartz filters (8 inch by 10 inch) using the protocol established by the National Ambient Air Quality Standards (NAAQS) for particulate matter. Filters were collected daily and sent to CDPHE in a manila envelope for laboratory analysis. The laboratory used the standards of protocol for PM_{10} gravimetric analysis that determines particulate concentration based on weight difference (35). PM_{10} level data are reported to CAPCD and stored in the environmental data warehouse within CDPHE. CAPCD analyzes the PM_{10} levels to identify samples with levels exceeding 150 $\mu g/m^3$ which are further analyzed for elemental and chemical composition (35). Data from the monitor at the municipal site were more complete (11.2% of daily values missing for Adams, 6.7% for municipal building, with no apparent trend for missing data for either site), the PM_{10} concentrations from these monitors were well correlated (r=0.88 on untransformed scale and r=0.81 on natural log of concentrations) over the study period based on days when both had readings. Due to the strong agreement between monitors and because the municipal monitor data were more complete, the statistical modeling incorporated PM_{10} concentrations from the municipal monitor only.

PM2.5 is not monitored in the San Luis Valley and therefore was not include in this study.

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Statistical Analyses

For each count outcome, a generalized linear model was fit using a log link, including a scale parameter for dispersion and employing generalized estimating equations to account for serial correlations in hospital counts over time. The *m*-dependent working covariance structure with *m*=4 was selected as the best available structure, allowing a flexible correlation structure between counts for days up to 4 days apart (22). Cubic b-splines were used to model the mean number of counts over time, using evenly spaced knots one year apart. Model predictors included class variables for day of the week and month, and continuous variables for daily temperature, pressure, and humidity. Wind speed was initially included but dropped due to weaker significance. Daily visit counts were determined by counting the number of visits per day in total and then by key strata [age category: 5-14, 15-64, 65+; disease category: asthma (493.x)]. We examined 1-, 3-, and 5-day moving averages of regular of log-transformed PM_{10} concentrations. For the 3 and 5-day moving averages, models related the count outcome on a given day to the average PM_{10} concentration over days up to and including that day (e.g., a count today was related to the average of PM_{10} today, yesterday and two days ago, for the lagged 3-day moving average (MA)). For individual-day PM_{10} (i.e., 1-day average), we examined up to lag 4 of the pollutant. Models were also fit using indicators for 1, 3 or 5-day averages that exceeded 50 and 100 μ/m^3 thresholds. Model-based standard errors were used, as the empirical standard errors could not be estimated for these data. For specific counts of children with asthma, the outcome was modeled as binary (0 versus at least 1) since counts were rare and a logit link was used. The supplement describes sensitivity analyses for models using 3 or 5-day MA pollutant variables that consider different ways of handling missing data.

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Results

EUH Visit Counts

From 2003 through 2012, there were 6958 total urgent and emergent visits; 3375 (48.5%) were associated with asthma, 2006 (28.8%) with pneumonia, 1345 (19.3%) with pharyngitis/nasopharingitis, and the remaining 231 (3.3%) with bronchitis. The median number of visits per day was 2 for all respiratory conditions (1 for asthma) with a range of 0 to 11 (0 to 7 for asthma). The mean age of patients was 35.7 years; 13.1% were 5-14 years, 52.4% were 15-64 years, and 18.9% were 65 years or older. The distribution of patients by age was similar to the age distribution in the SLV (Table 1). Our dataset did not include race/ethnicity or gender, however given that the dataset included all EUH from the region's only emergent/urgent care provider and hospital, it is expected that the study cohort is representative of the patient population of the region. Urgent and emergent care visits due to asthma had the highest occurrence on Sunday and Monday and during the months of February, September, and October. Table 2 shows means and standard deviations for hospital counts for the two monitors, by day of week, month and year. Preliminarily, we fit the daily all respiratory related EUH visit count data and daily PM_{10} levels using local polynomial regression (a type of nonparametric regression, Figure 1). The data show mean trends that coincided for the most part, and hospital count peaks that tended to occur every other year. Figure 2 shows estimated (mean) visit counts over time, adjusted for PM_{10}, meteorological and seasonal variables. The fitted curve is consistent with the descriptive curve for counts in Figure 1 and generally reflect a 2-year cycle in count behavior.

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PM_{10} and Meteorological Data

The IQRs of 1-, 3-, and 5-day averaged PM_{10} values from the municipal monitor were 16.0, 14.7, and 14.4, respectively. Both 3-day and 5-day averaged PM_{10} exceeded 50 μ/m^3 on 6.0% of days during the study period and exceeded 100 μ/m^3 on 0.7% of days. Geometric mean and geometric SD of PM_{10} concentrations by year, month, and day of week are shown in Table 2, while Table 3 shows a composite summary of pollution and meteorological variables.

Relationships between All Respiratory EUH Visits and PM_{10}

We completed an initial analysis of all respiratory conditions for patients of all ages with PM_{10} untransformed, which showed that for each IQR increase (15 $\mu g/m^3$) of 3-day average PM_{10} in outdoor air there was an associated increase of 1.8% (p=0.09) in daily hospital visit counts. For 5-day averaged PM_{10}, the findings were similar, with 2.3% (p=0.07) increase in daily hospital visit counts for all respiratory disease. When the 3-day average PM_{10} exceeded 100 $\mu g/m^3$ (modeling pollutant as binary), hospital visits for all respiratory diseases was 32.6% (p=0.03) higher than when it did not. Similarly, when the 5-day average exceeded 100 $\mu g/m^3$, hospital visits for all respiratory diseases was 40.0% (p=0.01) higher than when it did not. Analyses using individual-day pollutant variables up to lag 4 or log scale of pollutant variables did not yield significant results at the α=0.05 level.

Relationships between EUH Visits for Asthma and PM_{10}

In models for patients of all ages with PM_{10} untransformed, we observed that for each IQR increase (15 $\mu g/m^3$) in lagged 3-day average PM_{10} there was an associated increase of 3.1%

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(p=0.03) in daily EUH visit counts for asthma (Table 4). For 5-day moving average PM_{10}, the findings were similar, with 3.1% (p=0.06) increase in asthma-attributable EUH visits (Table 4). When 3-day moving average was log transformed, the direction of the findings remained, although not statistically significant (Table 4).

When the association was examined using binary PM_{10} concentrations, where the 3-day average PM_{10} exceeded 50 $\mu g/m^3$, there were 16.8% (p=0.03) more EUH asthma visits (Table 5). Similarly, when the 3-day average PM_{10} exceeded 100 $\mu g/m^3$, asthma visits were 65.8% (p=0.002) higher. When the 5-day pollution average exceeded 50 $\mu g/m^3$, there were 16.8% (p=0.03) more asthma-related EUH visits than when it did not (Table 4). Similarly, when the 5-day average exceeded 100 $\mu g/m^3$ asthma related EUH visits were 45.0% (p=0.03) higher (Table 5). Analyses using individual-day pollutant variables up to lag 4 or log scale of pollutant variables did not yield significant results at the α=0.05 level.

Discussion

In this longitudinal study, increased PM_{10} levels were associated with an increase in EUH visits related to respiratory conditions, especially asthma, for individuals 5 years and older. The greater significance of these binary variables at specific cut points compared to the continuous variables suggests that there may be a threshold effect, below which little or no pollution effect occurs. This was confirmed in follow-up analyses with change-point models, where the linear relationship between hospital counts and PM_{10} below 50$\mu g/m^3$ was very weak and insignificant. Both of the cut points used in our analyses are at an ambient air concentration less than the

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current EPA air quality standard for PM_{10} of 150 μg/m^3. Our observations in those affected by asthma were supported by similar findings in EUH visits related to all forms of respiratory conditions, suggesting that elevated PM_{10} levels in ambient air is associated with compromised lung health.

Plausible mechanisms for PM_{10} provoking respiratory illnesses are related to its pro-inflammatory properties. In asthma, this pro-inflammatory response causes increased airway hyper-responsiveness culminating in airway narrowing and the experience of asthma symptoms (23, 24). Experimental studies reveal that exposure to PM_{10} can cause alveolar cytokine release responsible for bronchospasm and reduced pulmonary function (25) and also known to cause epithelial injury resulting from its oxidative properties (23). It is suggested that this is because PM10, in contrast to gaseous pollutants can induce oxidative reactions by crossing the fluid in the respiratory track lining (39).

Epidemiologic research suggests that large (PM_{10}) particles can become lodged in the airways of the lungs causing compromised breathing, inevitably leading to worsening asthma, the possible need for requiring medical intervention. Studies have documented an association between higher PM_{10} levels in ambient air and increased number of emergency room visits (5, 11, 15, 38); a systematic review of 25 studies (8) also corroborated an association between PM_{10} levels in ambient air and increased number of emergency room visits and a second review found 2% increases in asthma related hospitalizations for every 10 μg/m^3 increase in PM_{10} (36) which was substantiated in another large systemic review by Weinmayr et. al. (2010), which found PM10 significantly increased risk for asthma symptoms (OR= 1.028; 95%CI: 1.006-1.051) (37). Lastly, a study by Canova et al. 2012 found that an increase in PM_{10} levels by 10 μg/m^3

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was associated with an 35% increase in emergency room visits due to asthma lagged 0-3 days (for lag 0-3, OR = 1.35 95%CI:1.04-1.76) similar to findings in this study (35).

Several factors place children at greater risk for asthma exacerbations due to elevated PM_{10} levels in ambient air and include: rapid growth and development during childhood (26), immature and under-developed lungs (27-29), higher inhaled air capacity, which can potentially lead to higher doses of PM_{10} (30), and a corresponding higher volume-to-body weight ratio than adults (29). Due to their smaller airways, the disposition of pollutants, especially PM_{10}, is greater in children than adults (28, 29) thus further supporting the significance of the findings that ambient PM_{10} levels increase EUH visits in children especially in rural areas where dust levels are elevated.

This study is not without limitations. It is expected that the use of a single monitor can approximate individual level potential for exposure, however, does not account for individual dose, which is variable due to volume of air intake, spatial variability in dust concentrations, indoor air PM_{10} concentration, time spent indoors verses outdoors, and time spent at other locations such as school, daycare or work. However, given the concordance between the two PM_{10} monitors present in Alamosa, the use of the municipal monitor for a population-level approximation of exposure is appropriate. Additionally, we only considered PM_{10} concentrations and did not consider other pollutants with known association with asthma exacerbations in urban populations, including nitrogen oxide (NO_x) and sulfur dioxide (SO_x) (31, 32). These other pollutants were not included because PM_{10} is the predominant ambient air pollutant of concern in this rural community and has never reported exceedances of NO_x or SO_x during the ten-year study period, whereas PM_{10} had 72 exceedances.

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Another limitation is that our statistical models did not account for individual-level confounders that could influence the need for EUH visit for worsening asthma. Factors such as underlying severity of chronic respiratory illnesses, smoke exposure, adherence to treatment plans, genetic susceptibility, respiratory infections (viral and bacterial), other household exposures, residential distance from clinic or hospital, and access to transportation all of which can increase the risk of exacerbations, were not included as part of the data ascertainment. These data were not included as part of the data sharing agreement with the regional medical facility as a means of preserve confidentiality since the data included individual records with some days having only one record. Future research in the area should collect individual level data that includes these other known triggers of asthma exacerbation as part of the prospective study that concurrently tracks air quality and medical care utilization related to asthma.

Another limitation is that $PM_{2.5}$ was not included in this analysis because it is not measured in the San Luis Valley. $PM_{2.5}$ has been associated with asthma exacerbation, however it is inconclusive as to whether asthma outcomes are worse with PM_{10} or with $PM_{2.5}$ or whether the mixed effects of both have even worse outcomes (41). It is possible that the exclusion of $PM_{2.5}$ from the statistical analysis induced bias however, it is not expected that this bias was differential. In rural areas during dust storms particulate matter of all sizes has been shown to increase, however PM_{10} increases the most at a factor of 4.7 whereas $PM_{2.5}$ and PM_1 only by a factor of two suggesting that in rural dust storms similar to the ones that plague the San Luis Valley, PM_{10} will increase more than other particulate matter (40). In a pilot study as part of this research, we completed a chemical composition analysis of PM_{10} quartz filters (n=75) with daily average levels > 75 µgm3. Results found that 16.5% of the filters had no detectable levels

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of polyaromatic hydrocarbons (PAH), a known pollutant due to traffic and wood burning and in 85% of samples only one PAH metabolite was detected. Results suggested that traffic and wood burning were not major contributions to air pollution which are also common sources of smaller particulate matter.

A final limitation is defining our cases based on ICD9 codes that were listed at time of discharge and then as the primary ICD9 code during the visit. ICD9 codes have been shown to underrepresent asthma cases, especially in young children due to complexity and misdiagnoses with lower respiratory infections which is why we excluded children under 5 years old (33). Bias due to case identification through ICD9 code is more readily noted in children under five years due to the apprehension of labeling a child of this age with asthma (34). However, a strength of this work is that the study did not involve children under the age of five, for this reason and limits this potential issue.

Even with these limitations, this study provides significant results and insights in that asthma exacerbations were associated with PM_{10} levels in a rural population and that the association is strongest in the pediatric population. Our work suggests that exposure to PM10 at thresholds lower than those currently set by the EPA (150 $\mu g/m^3$) may contribute to greater EUH visits related to asthma over a 24 hour period of time. This suggests the need for continued evaluation of the public health relevance of clean air standards. In conclusion, we observed an association between EUH visit and hospitalization counts and ambient air PM_{10} levels in a rural community prone to dust storms and EPA exceedances. Because PM_{10} in ambient air remains a common exposure in the United States, the impact on asthma and lung

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health should provide motivation to public health officials to conduct further research to elucidate the role of PM_{10} in respiratory health for individuals of all age.

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Figure Legends:

Figure 1. Local polynomial regression for daily PM_{10} (solid, left y-axis) and hospital counts (dashed, right y-axis) over a 10-year period (2003-2012). (First degree polynomial, with a smoothing parameter of 0.15 for both variables)

Figure 2. Estimated emergent/urgent visits and hospitalization counts from 2003-2012 based on nonparametric regression fit (dashed), and via GzLM fit (solid). The GzLM fit accounted for variables as described in the Statistical Analysis section.

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Table 1: Demographic distribution for the San Luis Valley Population (2010) and study cohort (2003-2012). Entries are count (percentage).

	San Luis Valley	Study Cohort
	n=46,173*	**3376 asthma-related EUH visits**
Age Group		
<5 years	1,755 (3.8%)	384 (11.4%)
5-14 years	3,114 (6.7%)	487 (14.4%)
15-64 years	36,086 (78.1%)	2062 (61.1%)
≥ 65 years	5,218 (11.3%)	443 (13.1%)
Race/Ethnicity		Not available
White non-Hispanic	23,087 (50%)	
Hispanic	21,701 (47%)	
Other	1,385 (3%)	
Gender		
Male	22,625 (49%)	
Female	23,548 (51%)	

*US Census American FactFinder https://factfinder.census.gov/faces/nav/jsf/pages/index.xhtml Accessed September 1, 2017

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Table 2: Mean (SD) for total and asthma related emergent/urgent and hospital visits; geometric mean (geom. SD) for PM_{10} concentrations ($\mu g/m^3$), by day of week, month and year, 2003-2012.

	Total EUH visits	Asthma EUH visits	PM_{10} ($\mu g/m^3$), Adams	PM_{10} ($\mu g/m^3$), Municipal
		Day of week		
Sunday	2.26 (1.65)	1.00 (1.13)	15.4 (1.84)	18.3 (1.84)
Monday	2.01 (1.59)	0.99 (1.06)	18.5 (1.82)	22.6 (1.70)
Tuesday	1.86 (1.52)	0.94 (1.09)	19.2 (1.74)	24.9 (1.66)
Wednesday	1.86 (1.47)	0.93 (1.00)	20.4 (1.81)	25.4 (1.78)
Thursday	1.74 (1.51)	0.91 (1.09)	20.0 (1.84)	25.2 (1.78)
Friday	1.84 (1.64)	0.89 (1.09)	19.1 (1.78)	24.7 (1.71)
Saturday	1.76 (1.43)	0.81 (0.96)	17.3 (1.85)	21.5 (1.71)
		Month		
Jan	2.03 (1.44)	0.89 (0.97)	19.9 (1.78)	24.4 (1.78)
Feb	2.78 (1.91)	1.15 (1.22)	16.1 (1.91)	22.2 (1.80)
Mar	2.44 (1.67)	0.97 (1.09)	16.6 (1.91)	21.4 (1.75)
April	1.95 (1.53)	0.88 (1.03)	19.8 (2.15)	24.4 (2.10)
May	1.84 (1.37)	0.85 (0.92)	19.2 (1.96)	24.1 (1.84)
June	1.66 (1.36)	0.80 (0.93)	23.2 (1.78)	28.8 (1.67)
July	1.38 (1.24)	0.76 (0.93)	17.9 (1.50)	22.5 (1.51)
Aug	1.47 (1.31)	0.78 (0.90)	16.6 (1.40)	19.1 (1.49)

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Sep	1.88 (1.48)	1.10 (1.13)	16.5 (1.51)	19.6 (1.51)
Oct	1.95 (1.72)	1.10 (1.29)	17.2 (1.86)	20.7 (1.80)
Nov	1.81 (1.51)	0.95 (1.13)	21.2 (1.90)	27.7 (1.80)
Dec	1.75 (1.52)	0.89 (1.09)	18.8 (1.91)	23.8 (1.77)
		Year		
2003	1.91 (1.54)	0.84 (0.98)	20.5 (1.79)	22.7 (1.71)
2004	1.56 (1.28)	0.74 (0.90)	18.5 (1.66)	20.6 (1.71)
2005	2.00 (1.48)	0.89 (0.94)	16.9 (1.84)	20.6 (1.72)
2006	1.93 (1.50)	0.81 (0.98)	16.8 (1.91)	21.4 (1.80)
2007	2.27 (1.56)	1.00 (1.06)	18.3 (1.77)	24.2 (1.79)
2008	1.82 (1.61)	0.71 (0.95)	16.8 (1.86)	23.1 (1.75)
2009	2.07 (1.68)	1.01 (1.15)	17.2 (1.80)	21.3 (1.69)
2010	1.74 (1.29)	0.84 (0.94)	18.4 (1.93)	22.1 (1.75)
2011	2.45 (1.70)	1.61 (1.36)	20.5 (1.77)	30.8 (1.77)
2012	1.31 (1.55)	0.79 (1.01)	21.3 (1.79)	26.0 (1.73)

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Table 3: Descriptive Statistics for PM_{10} and Meteorological Variables

Variable	Mean	SD*	Minimum	25th %-ile	50th %-ile	75th %-ile	Maximum
Temperature (°F)	42.7	18.2	-12	29	44	59	74
Pressure (altimeter inches)	22.8	0.16	22.06	22.68	22.81	22.9	23.17
Precipitation (inches)	0.019	0.074	0	0	0	0.005	1.49
Wind (miles per hour)	7.2	3.91	0	4.4	6.4	8.9	27.4
1-day PM10 (µg/m^3)	27.5	24.7	2	16	23	32	635
3-day PM10 (µg/m^3)	27.7	18.1	4	17.7	24	32.3	337.5
5-day PM10 (µg/m^3)	27.8	16.2	4.5	18.3	24.6	32.7	266
log 1-day PM10 (µg/m^3)	3.14	0.57	0.69	2.77	3.14	3.47	6.45
log 3-day PM10 (µg/m^3)	3.14	0.47	1.39	2.82	3.14	3.44	5.47

*SD: standard deviation

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Table 4: Generalized estimating equation estimates (95% CI) of change in asthma-related emergent/urgent and hospitalization visit count as a function of PM_{10} measured in $\mu g/m^3$

Lag structure for PM_{10}*	Records available for analysis	Relative increase in hospital count per IQR increase in pollutant†	95% CI	p-value
3-day MA	3445	3.1%	(0.3%, 5.9%)	0.03
3-day MA**	3444	3.9%	(0.9%, 6.8%)	0.01
5-day MA	3512	3.1%	(-0.1%, 6.4%)	0.06
1-day, lag 0	3112	1.0%	(-1.1%, 3.1%)	0.40
1-day, lag 1	3112	1.5%	(-0.6%, 3.4%)	0.17
1-day, lag 2	3111	1.5%	(-0.6%, 3.4%)	0.17
1-day, lag 3	3111	0.0%	(-2.2%, 2.3%)	0.99
1-day, lag 4	3110	-0.3%	(-2.5%, 2.1%)	0.81

*averaged days starting from current day, e.g., lagged 3-day MA includes current day plus previous 2 days.
**without outlier (1 value that exceeded 300 μ/m^3)
†IQR=16, 14.7 and 14.4 for 1-day, 3-day and 5-day moving averages, respectively.
CI: Confidence Interval

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Table 5: Estimates of change in asthma related emergent/urgent and hospital visit counts for high versus low PM_{10} measured in $\mu g/m^3$.

Lag structure for PM_{10}*	Cut point for PM_{10} ($\mu g/m^3$)	Records available for analysis	Relative increase in hospital count for 'high' versus 'low' pollution	95% CI	p-value
3-day MA	50	3445	16.8%	(1.2%, 34.8%)	0.03
3-day MA	100	3445	65.8%	(20.2%, 128.7%)	0.002
5-day MA	50	3512	14.1%	(-2.3%, 33.3%)	0.10
5-day MA	100	3512	45.0%	(2.7%, 104.8%)	0.03

*averaged days start from current day, e.g., lagged 3-day MA includes current day plus previous 2 days.
†IQR=14.7 for 3-day moving average, 14.4 for 5-day.
CI: Confidence Interval

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Figure 1: Local polynomial regression for daily PM_{10} (solid, left y-axis) and hospital counts (dashed, right y-axis) over a 10-year period (2003-2012). (First degree polynomial, with a smoothing parameter of 0.15 for both variables)

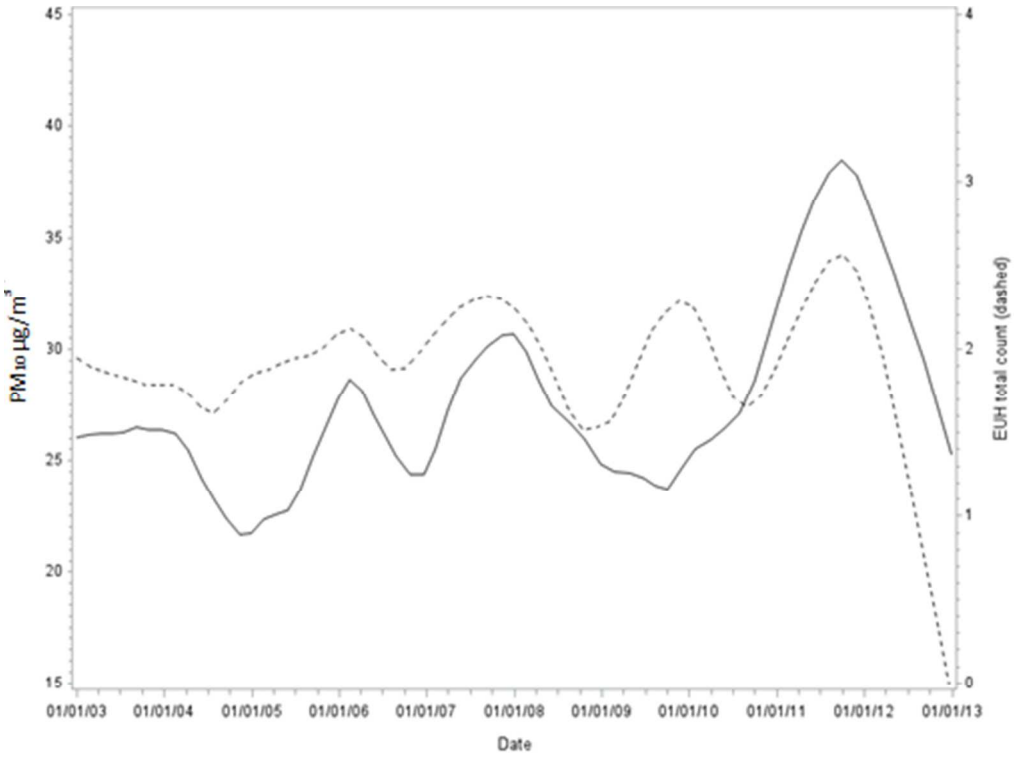

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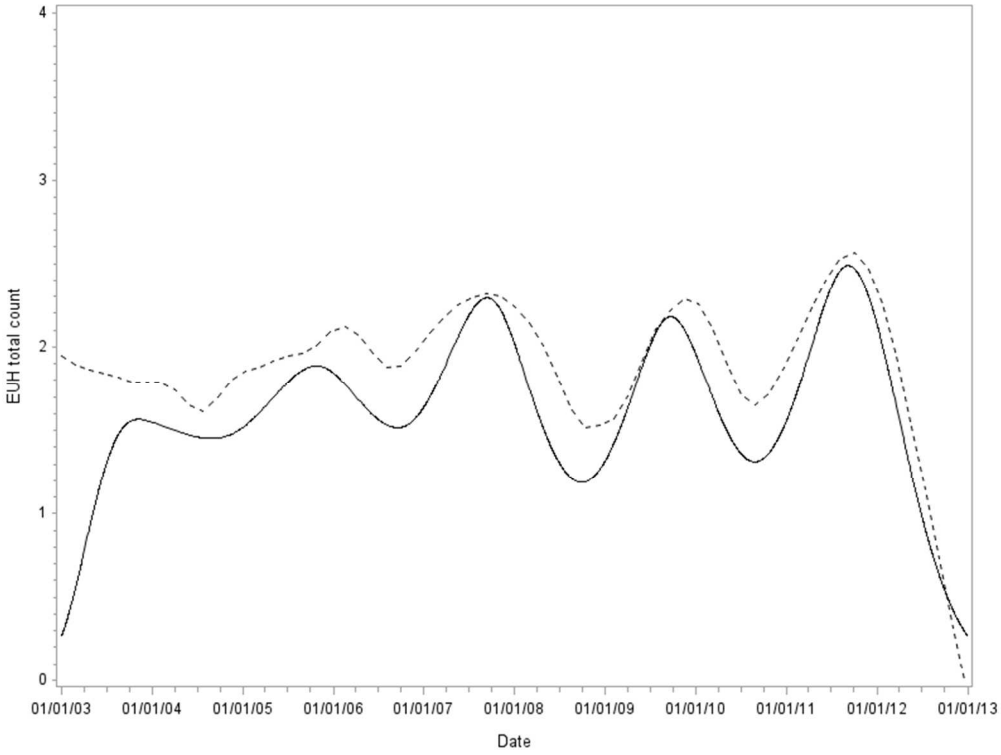
Figure 2: Estimated emergent/urgent and hospitalization counts from 2003-2012 based on nonparametric regression fit (dashed), and via GzLM fit (solid). The GzLM fit accounted for variables as described in the Statistical Analysis section.



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Online Data Supplement

Health Services Utilization in Asthma Exacerbations and PM_{10} Levels in Rural Colorado

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Methods

Handling missing data in 3 or 5-day MA variables

The pollution variables for the 10-year data have some days with missing values. Due to this, there are different ways the MA variables can be constructed or dealt with in the models that may impact results. To examine this, we considered two models for asthma counts, one using 3-day MA of PM_{10} and the other using the binary cut point of 50 micrograms/m3 of this variable. In the manuscript we used the average of all available records in the 3-day moving average. So, for example, if today's and yesterday's pollution values were available but not the preceding day, the average would still be calculated using those two available days. A second approach is to only calculate the average if all 3 records are available, and a third is to use the average that uses all available records, but include a weight statement in the PROC GENMOD code to indicate how many records were used in the average. Below is a summary of the 3 approaches for the two models considered.

Model	Approach	Effect estimate*	Records used	p-value
3-day MA PM_{10}	Average of all available records	3.1%	3445	0.03
	Set to missing if not all 3 records were available	3.4%	2648	0.07
	Average of all available records, weight by number of records used in calculation.	3.0%	3445	0.04
50 $\mu g/m^3$ cut of the 3-day MA of PM_{10}	Average of all available records	16.8%	3445	0.03
	Set to missing if not all 3 records were available	18.5%	2648	0.05
	Average of all available records, weight by number of records used in calculation.	16.5%	3445	0.04

*For the 3-day MA, these are increases in asthma hospital counts per IQR increase in PM10; for the 50 $\mu g/m^3$ cut of the 3-day MA of PM_{10}, estimates are increase in asthma counts when the pollutant is above the cut point versus below.

The results demonstrate little variation in estimates between the approaches. The 2nd approach that omitted values if they did not have all 3 days incorporated into the average had slightly higher estimates, but slightly smaller p-values due to the decreased number of records available for analysis.

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