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Changes in the acute response of respiratory diseases to $PM_{2.5}$ in New York State from 2005 to 2016

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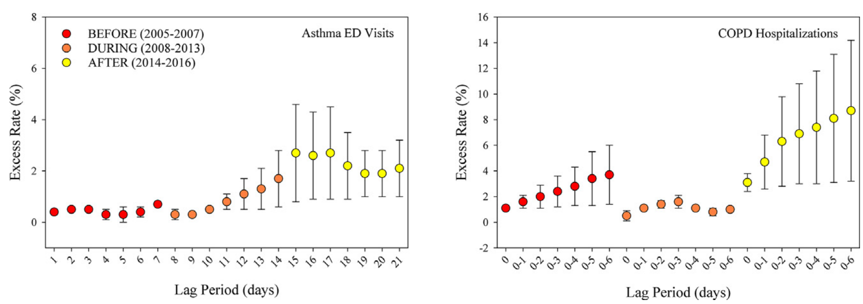
HIGHLIGHTS

- Increases in $PM_{2.5}$ result in increased asthma and COPD hospitalizations and ED visits.
- Across NYS, PM2.5 and these adverse health outcomes decreased from 2005 to 2016.
- The excess rate per unit PM mass for asthma ED visits increased in 2014–16.
- The excess rate per unit PM mass for COPD hospitalizations also increased in 2014–16.

GRAPHICAL ABSTRACT



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ABSTRACT

Prior studies reported that exposure to increased concentrations of fine particulate matter ($PM_{2.5}$) were associated with increased rates of hospitalization and emergency department (ED) visits for asthma and chronic obstructive pulmonary disease (COPD). In this study, rates were examined from 2005 to 2016 using a case-crossover design to ascertain if there have been changes in the rates per unit mass exposure given substantial reductions in $PM_{2.5}$ concentration and changes in its composition. $PM_{2.5}$ concentrations were reduced through a combination of policies designed to improve air quality and economic drivers, including the 2008 economic recession and shifts in the relative costs of coal and natural gas. The study period was split into three periods reflecting that much of the emissions changes occurred between 2008 and 2013. Thus, the three periods were defined as: BEFORE (2005 to 2007), DURING (2008–2013), and AFTER (2014–2016). In general, the number of hospitalizations and ED visits declined with the decreased concentration of $PM_{2.5}$. However, the rate of COPD hospitalizations and asthma ED visits associated with each interquartile range increase in ambient $PM_{2.5}$ concentration was larger in the AFTER period than the DURING and BEFORE periods. For example, each 6.8 μg/m^3 increase in $PM_{2.5}$ on the same day was associated with 0.4% (0.0%, 0.8%), 0.3% (−0.2%, 0.7%), and 2.7% (1.9%, 3.5) increases in the rate of asthma emergency department visits in the BEFORE, DURING, and AFTER periods, respectively, suggesting the same mass concentration of $PM_{2.5}$ was more toxic in the AFTER period.

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1. Introduction

Airborne particulate matter, particularly with aerodynamic diameters <2.5 μm ($PM_{2.5}$), has been associated with a variety of adverse health effects as well as visibility reduction and climate change through increased radiational forcing (US EPA, 2018). Exacerbation of asthma and chronic obstructive pulmonary disease (COPD) are several of the adverse effects of short-term exposures to $PM_{2.5}$. Guarnieri and Balmes (2014) reviewed the literature published from Jan 1, 2009 to Feb 28, 2014 on the effects of ambient air pollution on asthma. They summarized that there exists substantial evidence for the effect of ambient levels of PM exacerbating existing asthma, particularly by contributing to oxidative stress and allergic inflammation, and identified some evidence supporting PM as a cause of new cases of asthma. Orellano et al. (2017) summarized the literature on ambient air pollution and asthma published between January 2000 and October 2016. They also concluded that their meta-analysis provided evidence that there was an association between selected air pollutants and asthma exacerbations for differing lags. Anenberg et al. (2018) estimated that in 2015, 5 to 10 million annual asthma emergency department (ED) visits globally could be attributable to exposure to $PM_{2.5}$.

For COPD, Li et al. (2016) performed a systematic search in both English and Chinese electronic databases through March 30, 2016 and concluded that there was significant acute exacerbation of COPD by short-term exposure to air pollutants. Bloemsma et al. (2016) reviewed the literature on panel studies of COPD and concluded that particulate matter air pollution statistically significantly reduced lung function in patients with COPD enrolled in a panel study.

Thus, the associations of exacerbations of asthma and COPD with elevations in short-term exposures to $PM_{2.5}$ are well established. It would then be anticipated that as the $PM_{2.5}$ concentrations decreased, there would be a concurrent reduction in ED visits and hospitalizations for these respiratory diseases. Squizzato et al. (2018a) have examined the trends in air pollutants across New York State (NYS) during the period of 2005 to 2016 and found substantial reductions in the concentrations of all criteria pollutants except ozone. These reductions are the result of both policy initiatives such as improved fuel quality and required emissions controls on new heavy-duty diesel on-road vehicles that have reduced local emissions. Upwind pollution source emissions have also been reduced through actions by the Government of Ontario to eliminate the use of fossil fuels in electricity generation, and various U.S. Governmental actions such as the Cross-States Air Pollution Rule and settlements of lawsuits with electricity generators to reduce their emissions. In addition, economic factors such as the 2008 recession resulted in reduced demand for electricity and goods transport. The changes in the relative prices of coal and natural gas used to generate electricity has led to a switch in fuels as demand for electricity increased following the recession (Squizzato et al., 2018a). The major reductions in $PM_{2.5}$ have been in the concentrations of sulfate, nitrate, and elemental and organic carbon. The one component of $PM_{2.5}$ that has shown increases in recent year is secondary organic carbon (Zhang et al., 2018).

Recent work (Zhang et al., 2018; Croft et al., 2019) has found that although the overall rates of hospitalizations and ED visits for cardiovascular outcomes and respiratory infections have decreased, there have been increases in the toxicity of $PM_{2.5}$ with respect to some specific diseases. Zhang et al. (2018) reported that from 2014 to 2016, the same interquartile range of $PM_{2.5}$ mass was associated with a higher rate of ischemic heart disease events than in the 2005 to 2007 and 2008 to 2013 periods. These three periods were chosen based on the level of activity that reduced air pollutants emissions. These activities included regulatory actions that required cleaner fuels, additional control on motor vehicles, and reduced emissions from coal-fired power plants. In addition, economic drivers such as the 2008–09 recession and the changes in the relative costs of coal and natural gas had a significant effect on air quality. These activities and the resulting trends in air pollutants across NYS were documented by Squizzato et al. (2018a).

The, BEFORE (2005–2007) represented a period of limited changes before many of the regulations went into effect and prior to the recession. DURING (2008–2013) was the period that included the recession, substantial changes in fuel sulfur content, and the make-up of gasoline as well as transition from coal to more natural gas generated electricity driven by the low price of fracked natural gas. The AFTER period followed the period of changes although some further changes were occurring such as new light- and heavy-duty vehicles penetrating into the fleet. Croft et al. (2019) found increased rates of healthcare encounters for culture negative pneumonia and influenza were associated with increases in $PM_{2.5}$ concentrations in the previous few days, with the largest relative rate in the AFTER period compared to the DURING and BEFORE periods. In both studies, the authors noted that the change in composition from being dominated by secondary inorganic constituents to increased concentrations of secondary organic carbon may have influenced the observed changes in the relative toxicity of $PM_{2.5}$.

Thus, the present study examined whether similar changes in the rates of hospitalization or ED visits for asthma or COPD in adults associated with increases in $PM_{2.5}$ concentrations had similarly occurred over these three defined time intervals. The aim of this study was to determine the rates of hospitalization and ED visits across NYS for adult asthma and COPD patients associated with interquartile range increase in ambient $PM_{2.5}$ concentration and determine if those relative rates had changed over study period of 2005 to 2016.

2. Methods

2.1. Study population

From the Statewide Planning and Research Cooperative System (SPARCS) database, respiratory disease ED visits (patients treated and released home) or hospital admissions were retained for all adult New York residents (≥18 years of age) who lived within 15 miles of the Buffalo, Rochester, Albany, Bronx, Manhattan, or Queens $PM_{2.5}$ monitoring sites from January 1, 2005 to December 31, 2016. There were 384,720 hospitalizations and 863,605 ED visits available for analysis. However, the vast majority of these cases were for COPD or asthma and thus, we limited our study to these two diseases. We included subjects with a primary diagnosis (at time of hospitalization or ED visit) of asthma (ICD9 = 493; ICD10 = J45) or COPD (ICD9 = 491, 492; ICD10 = J41; J43). This study was reviewed and approved by the Institutional Review Board at the University at Albany, State University of New York.

2.2. Air pollution and weather

Hourly $PM_{2.5}$ concentrations at the six urban air-monitoring stations (Buffalo, Rochester, Albany, the Bronx, Manhattan, and Queens) were retrieved from the U.S. Environmental Protection Agency (https://aqs.epa.gov/api). Further details on measurement of $PM_{2.5}$, temperature, and relative humidity have been described previously (Zhang et al., 2018). For each subject, daily $PM_{2.5}$, temperature, and relative humidity values were assigned from the monitoring station closest to their residence.

2.3. Statistical analysis

To estimate the rate of asthma and COPD hospital admissions and ED visits associated with each interquartile range increase in $PM_{2.5}$ concentration on the same day (lag day 0), a time-stratified, case-crossover design (Maclure, 1991; Levy et al., 2001) was employed. We used data from all relevant hospital admissions near each of the 6 urban sites in a conditional logistic regression model in which a common exposure slope is assumed for all sites. This model regressed case–control status (i.e., case = 1, control = 0) against the mean $PM_{2.5}$ concentrations on case and control days, stratified on each asthma or COPD hospital admission matched set (1 case day and 3–4 control days, the same weekdays in the same month per subject/hospitalization). The methodology is described in detail by Zhang et al. (2018). Because case day and its matched control days are within a given month for each subject and a conditional analysis is conducted, non-time-varying confounders such as underlying medical conditions, long-term time trends, and season are controlled by design (Maclure, 1991; Levy et al., 2001). As is standard in case-crossover studies, the odds ratio estimated from this statistical model is a direct estimate of the rate ratio and its 95% confidence interval. The excess rate is then calculated as the percent increase in the rate per unit increase in $PM_{2.5}$ concentration (i.e. [rate ratio – 1.0] * 100%).

Temperature and relative humidity were included in the model using natural splines (4 degrees of freedom [df]), where the df values were determined using Akaike's information criterion (Aho et al., 2014). The same model was run separately for ED visits and hospitalizations for asthma and COPD using the mean $PM_{2.5}$ concentrations averaged over lag days 0–1, 0–2, 0–3, 0–4, 0–5, and 0–6 in separate models. Since 7 lag times were analyzed for each disease subgroup, statistical significance for the resulting slopes was defined as $p < 0.007$ (0.05/7). The lag time exposures were averaged over increasing numbers of days (i.e., 0–1, 0–2, etc.) rather than segmental lag days (i.e. day 1, day 2, day 3) were used to assess more accurately the excess rate pattern across lag times. Inference was made considering several factors, including the pattern of response across the lag averaging times, the precision of each estimate, and the statistical significance of each rate ratio.

Next, the changes in the association between $PM_{2.5}$ and the rate of asthma or COPD differed by period (BEFORE = 2005–2007, DURING = 2008–2013, AFTER = 2014–2016), were assessed by adding interaction terms of period with $PM_{2.5}$ to the model. The significance of the difference of the $PM_{2.5}$ effect across periods was evaluated by a 2 degrees-of-freedom test for interaction. If the interaction across period was statistically significant ($p \le 0.05$), the excess rates in the AFTER, DURING, and BEFORE periods were compared to determine if was any were, using $p = 0.017$ to determine the significance of the interaction term. All analyses were done using R version 3.5.1 (https://www.r-project.org/).

3. Results

3.1. Subjects

Tables 1a–1d present the characteristics of subjects and numbers of hospitalizations and ED visits, respectively, separated by diagnosis (asthma or COPD), site, and region (upstate and New York City (NYC)). The three NYC sites dominated the number of subjects. Thus, analyses were also done separately for the "upstate" sites (Albany, Buffalo, and Rochester) and the NYC sites (Bronx, Manhattan, and Queens) (Tables 1a–1d). The $PM_{2.5}$ concentrations measured at the upstate sites had higher fraction of secondary inorganic species compared to the NYC sites (Squizzato et al., 2018b). The upstate and NYC sites were affected by different sources. At the upstate sites, road salt was observed during the winter while in NYC, fresh and aged sea salt as well as residual oil sources were observed (Squizzato et al., 2018b).

For asthma, roughly two thirds of the patients were women, compared to an even split between genders in COPD. Patients hospitalized with COPD were much older (average age of 71 years) than patients with asthma (average age of 55 years). Patients treated and released from the ED (ED visits) were younger overall, but again COPD patients were older (average age of 62 years) than patients with asthma (average age of 40 years).

The upstate subjects with asthma were predominantly white. The largest race/ethnicity group for the Bronx and Manhattan subjects was black with substantial fractions of white and Hispanic patients. The majority of the Queens' subjects were white. The majority of COPD patients were white, with the exception of the Bronx and Manhattan, where the proportion of white and black subjects were essentially equal.

The frequency of hospitalizations for both COPD and asthma decreased over time, with the fewest recorded in 2016. The frequency of ED visits for COPD and asthma appeared stable over time, though again the fewest ED visits also occurred in 2016.

Tables S1 and S2 report the 15 most commonly listed comorbidities for those asthma and COPD patients, respectively, for both hospitalizations and ED visits. The comorbidities of the subjects hospitalized for asthma and COPD appeared similar with the notable exception of the much larger proportion of COPD patients than asthmatics with comorbid heart failure (45% vs. 20%) and chronic heart disease (31% vs. 13%). For patients treated and discharged from the ED, comorbidities appeared similar between asthma and COPD, though the proportion of patients with heart conditions was much lower. For COPD ED visits, only ~5% of subjects had heart failure or chronic heart disease, while for asthma, roughly 0.4% of subjects had cardiac disease.

3.2. Exposure

Table 2 presents the distributional characteristics of the $PM_{2.5}$ concentrations for each of the periods (BEFORE, DURING, and AFTER), for each of the six sites averaged for the subjects' case and control exposure periods. No counties in NYS were designated as out of attainment of the 24-hour or annual average National Ambient Air Quality Standards for $PM_{2.5}$ during the period of this study (https://www3.epa.gov/airquality/greenbook/mappm25both.html). With the Tapered Element Oscillating Microbalance (TEOM) measurement system, there are occasional negative values as semi-volatile constituents such as ammonium nitrate and organic matter are lost from the filter. The maximum observed $PM_{2.5}$ value was 59.6 μg/m^3 at the Manhattan site. Rochester had the lowest maximum value of 49.8 μg/m^3, and Albany had a maximum of 50.6 μg/m^3. Median exposures ranged from 6.9 to 12.2 μg/m^3 for the case periods and 6.7 to 12.0 μg/m^3 for the control periods. The variations in $PM_{2.5}$ concentrations over time are discussed in detail by Squizzato et al. (2018a).

3.3. Incidence rates

Table 3 gives the mean incidence rates (#/1000 persons per year) for hospital admissions and ED visits by period. Generally, the lowest hospitalization and ED visit rates occurred in the AFTER period showing the likely improvement in public health resulting from improved treatment and prevention efforts, as well as the reductions in ambient air pollution. However, for some outcomes in some locations (e.g., ED visits for COPD in Albany), there was an increase in these rates from BEFORE to DURING, and then a decline to AFTER. In general, the upstate areas had higher rates compared to the NYC sites.

3.4. Excess rates

Table 4 presents the excess rates (%), 95% confidence intervals, and probability that the value is different from 0 for hospital admissions and ED visits for asthma and COPD that are associated with each interquartile range (IQR) increase in $PM_{2.5}$ concentrations for the entire period integrated across all six sites. Hospitalizations for asthma and COPD and ED visits for asthma showed statistically significant increases with increasing $PM_{2.5}$ concentrations. The excess rates of ED visits for COPD were all positive, but none were statistically significant.

Table 5 presents the excess rates of asthma and COPD hospitalizations and ED visits associated with the same study period IQR increase in $PM_{2.5}$ concentrations for each of the three periods over the entire NYS for each of the lag days. Table 6 provides this same information separately by region (upstate and NYC). The final column in these tables provides the *p*-value for the test of interaction among the period-specific scaled rate ratio estimates. For asthma hospitalizations across

Table 1a
Characterization of the asthma patients requiring hospitalizations.

Variable	Albany (N)	Albany (%)	Bronx (N)	Bronx (%)	Buffalo (N)	Buffalo (%)	Manhattan (N)	Manhattan (%)	Queens (N)	Queens (%)	Rochester (N)	Rochester (%)	Upstate (N)	Upstate (%)	NYC (N)	NYC (%)
N	5499	100	88,298	100	7405	100	65,751	100	42,466	100	6757	100	19,661	100%	196,515	100%
Male	1509	27.44	26,392	29.89	1960	26.47	19,896	30.26	12,984	30.58	1812	26.82	5281	26.86	59,272	30.16
Age (years; mean, (SD))	53.22	(18.01)	54.03	(17.70)	56.17	(17.56)	56.33	(17.53)	57.59	(18.27)	53.39	(17.29)	54.39	(17.57)	55.57	(14.80)
18–39	1290	23.46	18,241	20.66	1286	17.37	11,115	16.90	6992	16.46	1381	20.44	3957	20.13	36,348	18.50
40–49	1148	20.88	16,862	19.1	1376	18.58	11,592	17.63	7074	16.66	1419	21.00	3943	20.05	35,528	18.08
50–59	1160	21.09	19,899	22.54	1697	22.92	15,145	23.03	8977	21.14	1631	24.14	4488	22.83	44,021	22.40
60–69	811	14.75	14,887	16.86	1236	16.69	11,693	17.78	7392	17.41	1082	16.01	3129	15.91	33,972	17.29
70–79	544	9.89	11,016	12.48	975	13.17	9279	14.11	6317	14.88	636	9.41	2155	10.96	26,612	13.54
>80	546	9.93	7393	8.37	835	11.28	6927	10.54	5714	13.46	608	9.00	1989	10.12	20,034	10.19
Race/ethnicity																
White	3267	59.41	14,356	16.26	4222	57.02	16,714	25.42	15,332	36.10	3205	47.43	10,694	54.39	46,402	23.61
Black	1483	26.97	29,616	33.54	2533	34.21	29,646	45.09	15,632	36.81	2573	38.08	6589	33.51	74,894	38.11
American Indian	8	0.15	399	0.45	25	0.34	301	0.46	333	0.78	7	0.10	40	0.20	1033	0.53
Asian	20	0.36	696	0.79	30	0.41	1553	2.36	1655	3.90	26	0.38	76	0.39	3904	1.99
Native Hawaii	3	0.05	14	0.02	2	0.03	12	0.02	24	0.06	2	0.03	7	0.04	50	0.03
Hispanic	315	5.73	29,148	33.01	371	5.01	13,805	21.00	6503	15.31	710	10.51	1396	7.10	49,456	25.17
Year																
2005	560	10.18	7386	8.36	750	10.13	5766	8.77	3975	9.36	586	8.67	1896	9.64	17,127	8.72
2006	530	9.64	7925	8.98	675	9.12	5833	8.87	3974	9.36	569	8.42	1774	9.02	17,732	9.02
2007	469	8.53	8037	9.1	658	8.89	5936	9.03	3830	9.02	568	8.41	1695	8.62	17,803	9.06
2008	484	8.8	8663	9.81	740	9.99	6292	9.57	3841	9.04	655	9.69	1879	9.56	18,796	9.56
2009	602	10.95	8946	10.13	821	11.09	6744	10.26	3857	9.08	698	10.33	2121	10.79	19,547	9.95
2010	527	9.58	8057	9.12	648	8.75	6314	9.60	3849	9.06	609	9.01	1784	9.07	18,220	9.27
2011	444	8.07	7694	8.71	661	8.93	6067	9.23	3868	9.11	592	8.76	1697	8.63	17,629	8.97
2012	447	8.13	7607	8.62	635	8.58	6124	9.31	3671	8.64	608	9.00	1690	8.60	17,402	8.86
2013	414	7.53	6962	7.88	530	7.16	5681	8.64	3424	8.06	532	7.87	1476	7.51	16,067	8.18
2014	422	7.67	6856	7.76	583	7.87	5017	7.63	3378	7.95	524	7.75	1529	7.78	15,251	7.76
2015	377	6.86	6034	6.83	457	6.17	3799	5.78	2948	6.94	495	7.33	1329	6.76	12,781	6.50
2016	223	4.06	4131	4.68	247	3.34	2178	3.31	1851	4.36	321	4.75	791	4.02	8160	4.15
Season																
Fall	1375	25	21,219	24.03	1809	24.43	15,410	23.44	10,030	23.62	1690	25.01	4874	24.79	46,659	23.74
Spring	1525	27.73	24,085	27.28	2148	29.01	17,854	27.15	11,533	27.16	1802	26.67	5475	27.85	53,472	27.21
Summer	1042	18.95	17,568	19.9	1472	19.88	13,465	20.48	8684	20.45	1451	21.47	3965	20.17	39,717	20.21
Winter	1557	28.31	25,426	28.8	1976	26.68	19,022	28.93	12,219	28.77	1814	26.85	5347	27.20	56,667	28.84
Length of stay (days; mean (SD))	4.08	(3.85)	3.79	(4.45)	4.24	(7.67)	4.06	(4.51)	4.37	(5.58)	3.50	(4.69)	3.94	(6.55)	4.01	(3.93)

Table 1b
Characteristics of patients visiting emergency departments for asthma.

Variable	Albany (N)	Albany (%)	Bronx (N)	Bronx (%)	Buffalo (N)	Buffalo (%)	Manhattan (N)	Manhattan (%)	Queens (N)	Queens (%)	Rochester (N)	Rochester (%)	Upstate (N)	Upstate (%)	NYC (N)	NYC (%)
N	26,062	100	341,437	100	34,363	100	250,027	100	123,938	100	26,808	100	87,233	100%	715,402	100%
Male	9873	37.88	135,727	39.75	12,787	37.21	101,234	40.49	48,754	39.34	9876	36.84	32,536	37.30	285,715	39.94
Age (years; mean, (SD))	37.94	(14.28)	40.97	(15.01)	39.63	(15.25)	41.49	(15.29)	40.64	(15.42)	38.82	(15.22)	38.85	(14.94)	41.02	(12.41)
18–39	15,075	57.84	161,706	47.36	18,352	53.41	117,002	46.80	61,366	49.51	14,696	54.82	48,123	55.17	340,074	47.54
40–49	5649	21.68	78,593	23.02	7278	21.18	56,029	22.41	26,637	21.49	5761	21.49	18,688	21.42	161,259	22.54
50–59	3401	13.05	62,686	18.36	5206	15.15	45,287	18.11	21,475	17.33	3688	13.76	12,295	14.09	129,448	18.09
60–69	1153	4.42	26,144	7.66	2093	6.09	21,015	8.41	9221	7.44	1652	6.16	4898	5.61	56,380	7.88
70–79	525	2.01	9413	2.76	887	2.58	8106	3.24	3656	2.95	622	2.32	2034	2.33	21,175	2.96
>80	259	0.99	2895	0.85	547	1.59	2588	1.04	1583	1.28	389	1.45	1195	1.37	7066	0.99
Race/ethnicity																
White	11,393	43.71	38,101	11.16	15,766	45.88	37,507	15.00	29,486	23.79	9873	36.83	37,032	42.45	105,094	14.69
Black	10,729	41.17	151,415	44.35	14,101	41.04	143,961	57.58	60,534	48.84	11,619	43.34	36,449	41.78	355,910	49.75
American Indian	32	0.12	1090	0.32	106	0.31	571	0.23	523	0.42	12	0.04	150	0.17	2184	0.31
Asian	97	0.37	1576	0.46	123	0.36	2449	0.98	3739	3.02	78	0.29	298	0.34	7764	1.09
Native Hawaii	10	0.04	54	0.02	6	0.02	24	0.01	70	0.06	1	0.00	17	0.02	148	0.02
Hispanic	1634	6.27	90,082	26.38	2315	6.74	37,980	15.19	20,443	16.49	3691	13.77	7640	8.76	148,505	20.76
Year																
2005	2028	7.78	27,987	8.2	2886	8.4	18,268	7.31	10,217	8.24	1916	7.15	6830	7.83	56,472	7.89
2006	2075	7.96	28,212	8.26	2846	8.28	17,821	7.13	10,428	8.41	1950	7.27	6871	7.88	56,461	7.89
2007	2154	8.26	28,796	8.43	2680	7.80	18,799	7.52	9324	7.52	1977	7.37	6811	7.81	56,919	7.96
2008	2269	8.71	28,941	8.48	2727	7.94	19,656	7.86	9634	7.77	2185	8.15	7181	8.23	58,231	8.14
2009	2230	8.56	27,807	8.14	3029	8.81	19,930	7.97	10,728	8.66	2255	8.41	7514	8.61	58,465	8.17
2010	2198	8.43	26,159	7.66	2898	8.43	21,407	8.56	10,817	8.73	2375	8.86	7471	8.56	58,383	8.16
2011	2328	8.93	26,099	7.64	2863	8.33	22,241	8.90	11,470	9.25	2352	8.77	7543	8.65	59,810	8.36
2012	2527	9.70	30,047	8.8	3143	9.15	24,449	9.78	12,615	10.18	2478	9.24	8148	9.34	67,111	9.38
2013	2304	8.84	30,745	9	3026	8.81	22,614	9.04	11,831	9.55	2440	9.10	7770	8.91	65,190	9.11
2014	2201	8.45	29,442	8.62	3027	8.81	21,878	8.75	9215	7.44	2458	9.17	7686	8.81	60,535	8.46
2015	1950	7.48	28,988	8.49	2758	8.03	22,176	8.87	9256	7.47	2328	8.68	7036	8.07	60,420	8.45
2016	1798	6.90	28,214	8.26	2480	7.22	20,788	8.31	8403	6.78	2094	7.81	6372	7.30	57,405	8.02
Season																
Fall	7546	28.95	87,689	25.68	9916	28.86	64,752	25.9	33,028	26.65	7690	28.69	25,152	28.83	185,469	25.93
Spring	6626	25.42	92,977	27.23	8738	25.43	69,325	27.73	34,016	27.45	6662	24.85	22,026	25.25	196,318	27.44
Summer	5717	21.94	70,212	20.56	7569	22.03	50,993	20.39	24,937	20.12	6142	22.91	19,428	22.27	146,142	20.43
Winter	6173	23.69	90,559	26.52	8140	23.69	64,957	25.98	31,957	25.78	6314	23.55	20,627	23.65	187,473	26.21
Length of stay (days; mean (SD))	0.10	(0.32)	0.05	(0.29)	0.14	(0.38)	0.06	(0.39)	0.08	(0.31)	0.26	(0.53)	0.16	(0.46)	0.06	(0.62)

Table 1c
Characteristics of the patients requiring hospitalizations for COPD.

Variable	Albany (N)	Albany (%)	Bronx (N)	Bronx (%)	Buffalo (N)	Buffalo (%)	Manhattan (N)	Manhattan (%)	Queens (N)	Queens (%)	Rochester (N)	Rochester (%)	Upstate (N)	Upstate (%)	NYC (N)	NYC (%)
N	13,447	100	41,561	100	16,070	100	45,427	100	41,277	100	10,762	100	40,279	100.00	128,265	100%
Male	5274	39.22	19,392	46.66	6316	39.3	21,798	47.98	19,025	46.09	4765	44.28	16,355	40.60	60,215	46.95
Age (years; mean, (SD))	69.45	(12.03)	70.40	(12.44)	70.74	(11.93)	71.03	(12.46)	72.98	(12.35)	70.03	(12.01)	70.12	(11.98)	71.45	(9.81)
18–39	53	0.39	275	0.66	69	0.43	306	0.67	208	0.5	47	0.44	169	0.42	789	0.62
40–49	590	4.39	1876	4.51	651	4.05	1838	4.05	1281	3.1	472	4.39	1713	4.25	4995	3.89
50–59	2411	17.93	6329	15.23	2306	14.35	6606	14.54	4851	11.75	1689	15.69	6406	15.90	17,786	13.87
60–69	3545	26.36	10,261	24.69	3986	24.8	10,629	23.40	8929	21.63	2863	26.6	10,394	25.81	29,819	23.25
70–79	3758	27.95	12,168	29.28	4858	30.23	13,473	29.66	11,910	28.85	3096	28.77	11,712	29.08	37,551	29.28
>80	3090	22.98	10,652	25.63	4200	26.14	12,575	27.68	14,098	34.15	2595	24.11	9885	24.54	37,325	29.10
Race/ethnicity																
White	11,424	84.96	17,022	40.96	13,201	82.15	25,862	56.93	27,376	66.32	8839	82.13	33,464	83.08	70,260	54.78
Black	966	7.18	11,528	27.74	2339	14.56	11,179	24.61	8369	20.28	1522	14.14	4827	11.98	31,076	24.23
American Indian	9	0.07	151	0.36	24	0.15	232	0.51	216	0.52	4	0.04	37	0.09	599	0.47
Asian	17	0.13	432	1.04	25	0.16	1577	3.47	1238	3	25	0.23	67	0.17	3247	2.53
Native Hawaii	2	0.01	8	0.02	1	0.01	7	0.02	19	0.05	1	0.01	4	0.01	34	0.03
Hispanic	590	4.39	6934	16.68	192	1.19	4610	10.15	2707	6.56	265	2.46	1047	2.60	14,251	11.11
Year																
2005	1358	10.1	3394	8.17	1520	9.46	4001	8.81	3663	8.87	1022	9.5	3900	9.68	11,058	8.62
2006	1370	10.19	3364	8.09	1388	8.64	3935	8.66	3753	9.09	946	8.79	3704	9.20	11,052	8.62
2007	1243	9.24	3683	8.86	1371	8.53	4013	8.83	3611	8.75	1010	9.38	3624	9.00	11,307	8.82
2008	1319	9.81	3998	9.62	1660	10.33	4444	9.78	4188	10.15	1187	11.03	4166	10.34	12,630	9.85
2009	1271	9.45	4229	10.18	1683	10.47	4392	9.67	4108	9.95	1086	10.09	4040	10.03	12,729	9.92
2010	1270	9.44	4203	10.11	1609	10.01	4317	9.50	4008	9.71	1020	9.48	3899	9.68	12,528	9.77
2011	1315	9.78	4071	9.80	1636	10.18	4457	9.81	4161	10.08	1068	9.92	4019	9.98	12,689	9.89
2012	1197	8.9	4049	9.74	1530	9.52	4646	10.23	4231	10.25	1024	9.51	3751	9.31	12,926	10.08
2013	1168	8.69	4000	9.62	1466	9.12	4376	9.63	3709	8.99	921	8.56	3555	8.83	12,085	9.42
2014	1099	8.17	3770	9.07	1274	7.93	3831	8.43	3367	8.16	806	7.49	3179	7.89	10,968	8.55
2015	830	6.17	2745	6.60	928	5.77	2961	6.52	2408	5.83	660	6.13	2418	6.00	8114	6.33
2016	7	0.05	55	0.13	5	0.03	54	0.12	70	0.17	12	0.11	24	0.06	179	0.14
Season																
Fall	3063	22.78	9147	22.01	3502	21.79	10,125	22.29	8943	21.67	2383	22.14	8948	22.22	28,215	22.00
Spring	3844	28.59	11,377	27.37	4681	29.13	12,384	27.26	11,189	27.11	2987	27.76	11,512	28.58	34,950	27.25
Summer	2788	20.73	9251	22.26	3274	20.37	10,013	22.04	9225	22.35	2303	21.4	8365	20.77	28,489	22.21
Winter	3752	27.9	11,786	28.36	4613	28.71	12,905	28.41	11,920	28.88	3089	28.7	11,454	28.44	36,611	28.54
Length of stay (days; mean (SD))	5.27	(6.13)	5.57	(7.50)	5.30	(6.20)	5.75	(6.89)	6.34	(6.89)	4.88	(7.06)	5.18	(7.39)	5.88	(5.73)

Table 1d
Characteristics of patients visiting the ED for COPD.

Variable	Albany (N)	Albany (%)	Bronx (N)	Bronx (%)	Buffalo (N)	Buffalo (%)	Manhattan (N)	Manhattan (%)	Queens (N)	Queens (%)	Rochester (N)	Rochester (%)	Upstate (N)	Upstate (%)	NYC (N)	NYC (%)
N	7406	100	15,699	100	10,166	100	13,693	100	7902	100	6104	100	23,676	100%	37,294	100%
Male	3107	41.95	8024	51.11	4174	41.06	7541	55.07	3948	49.96	2819	46.18	10,100	42.66	19,513	52.32
Age (years; mean, (SD))	62.64	(13.09)	62.02	(12.50)	63.73	(13.41)	62.17	(12.72)	63.95	(13.70)	64.09	(13.01)	63.48	(13.25)	62.48	(10.08)
18–39	215	2.90	468	2.98	289	2.84	430	3.14	256	3.24	98	1.61	602	2.54	1154	3.09
40–49	928	12.53	1652	10.52	1155	11.36	1569	11.46	786	9.95	691	11.32	2774	11.72	4007	10.74
50–59	2110	28.49	4891	31.15	2591	25.49	4056	29.62	2128	26.93	1622	26.57	6323	26.71	11,075	29.70
60–69	1838	24.82	4395	28.00	2667	26.23	3731	27.25	1953	24.72	1608	26.34	6113	25.82	10,079	27.03
70–79	1433	19.35	2832	18.04	2029	19.96	2612	19.08	1604	20.30	1167	19.12	4629	19.55	7048	18.90
>80	882	11.91	1461	9.31	1435	14.12	1295	9.46	1175	14.87	918	15.04	3235	13.66	3931	10.54
Race/ethnicity																
White	5928	80.04	3997	25.46	7320	72.00	5791	42.29	4251	53.80	4546	74.48	17,794	75.16	14,039	37.64
Black	988	13.34	7076	45.07	2288	22.51	5264	38.44	2391	30.26	1297	21.25	4573	19.31	14,731	39.50
American Indian	3	0.04	37	0.24	25	0.25	26	0.19	39	0.49	1	0.02	29	0.12	102	0.27
Asian	11	0.15	96	0.61	11	0.11	241	1.76	213	2.70	10	0.16	32	0.14	550	1.47
Native Hawaii	1	0.01	3	0.02	1	0.01	1	0.01	4	0.05	0	0.00	2	0.01	8	0.02
Hispanic	238	3.21	2430	15.48	202	1.99	1275	9.31	672	8.50	184	3.01	624	2.64	4377	11.74
Year																
2005	583	7.87	856	5.45	831	8.17	747	5.46	591	7.48	405	6.63	1819	7.68	2194	5.88
2006	685	9.25	1019	6.49	695	6.84	749	5.47	531	6.72	438	7.18	1818	7.68	2299	6.16
2007	511	6.90	962	6.13	659	6.48	842	6.15	478	6.05	473	7.75	1643	6.94	2282	6.12
2008	572	7.72	1195	7.61	735	7.23	940	6.86	560	7.09	529	8.67	1836	7.75	2695	7.23
2009	599	8.09	1369	8.72	776	7.63	1063	7.76	694	8.78	507	8.31	1882	7.95	3126	8.38
2010	581	7.84	1317	8.39	883	8.69	1218	8.90	816	10.33	493	8.08	1957	8.27	3351	8.99
2011	767	10.36	1388	8.84	987	9.71	1318	9.63	800	10.12	565	9.26	2319	9.79	3506	9.40
2012	784	10.59	1772	11.29	1023	10.06	1696	12.39	979	12.39	689	11.29	2496	10.54	4447	11.92
2013	879	11.87	1938	12.34	1276	12.55	1698	12.40	956	12.10	654	10.71	2809	11.86	4592	12.31
2014	823	11.11	2065	13.15	1224	12.04	1790	13.07	763	9.66	759	12.43	2806	11.85	4618	12.38
2015	618	8.34	1719	10.95	1038	10.21	1510	11.03	654	8.28	566	9.27	2222	9.39	3883	10.41
2016	4	0.05	99	0.63	39	0.38	122	0.89	80	1.01	26	0.43	69	0.29	301	0.81
Season																
Fall	1803	24.35	3740	23.82	2445	24.05	3329	24.31	1881	23.8	1504	24.64	5752	24.29	8950	24.00
Spring	1910	25.79	4018	25.59	2729	26.84	3592	26.23	2024	25.61	1621	26.56	6260	26.44	9634	25.83
Summer	1780	24.03	3985	25.38	2477	24.37	3353	24.49	1980	25.06	1512	24.77	5769	24.37	9318	24.99
Winter	1913	25.83	3956	25.20	2515	24.74	3419	24.97	2017	25.53	1467	24.03	5895	24.90	9392	25.18
Length of stay (days, mean (SD))	0.18	(0.54)	0.07	(0.36)	0.18	(0.49)	0.09	(0.35)	0.13	(0.39)	0.41	(0.75)	0.24	(0.63)	0.09	(0.68)

Table 2
Distributional characteristics of the $PM_{2.5}$ concentrations (μg/m^3).

		Case Periods							Control Periods						
Location	Period	min	5th	25th	median	75th	95th	max	min	5th	25th	median	75th	95th	max
Albany	Overall	-2	1.8	4.5	7.4	11.6	21.2	50.6	-2.0	1.8	4.5	7.4	11.5	20.9	50.6
	BEFORE	-1.1	2.1	5.4	8.8	14.5	25.8	50.6	-1.1	2.1	5.5	8.7	14.3	26.1	50.6
	DURING	-1.6	1.7	4.3	6.9	10.9	19.5	35.6	-1.6	1.8	4.3	6.9	10.7	19.0	35.6
	AFTER	-2.0	1.7	4.1	7.0	10.1	16.5	45.4	-2.0	1.6	4.2	7.0	10.3	16.1	45.4
Bronx	Overall	-3.3	2.6	5.8	9.0	13.8	24.6	58.2	-3.3	2.6	5.8	8.9	13.8	24.4	58.2
	BEFORE	-0.2	3.8	7.1	11.0	17.0	28.2	58.2	-0.2	3.9	7.0	10.9	16.9	27.9	58.2
	DURING	-3.3	2.3	5.6	8.8	13.2	23.1	53.4	-3.3	2.2	5.6	8.8	13.2	23.0	53.4
	AFTER	-0.1	2.8	5.0	7.5	10.8	17.1	30.2	-0.1	2.7	4.9	7.4	10.7	17.1	30.2
Buffalo	Overall	-2.7	2.6	5.8	8.8	12.9	22.9	56.1	-2.7	2.6	5.7	8.7	12.6	22.8	56.1
	BEFORE	-0.8	3.3	6.9	10.3	14.8	29.3	56.1	-0.8	3.3	6.8	10.0	14.3	28.9	56.1
	DURING	-2.7	2.5	5.6	8.4	12.1	21.3	44.0	-2.7	2.5	5.5	8.3	12.0	21.2	44.0
	AFTER	-2.0	2	5.2	8.2	11.9	18.9	29.1	-2.0	1.9	5.1	8.0	11.6	17.6	29.1
Manhattan	Overall	-2.0	4.2	7.3	10.7	15.3	25.3	59.6	-2.0	4.1	7.3	10.6	15.3	25.2	59.6
	BEFORE	0.6	4.9	8.3	12.2	17.8	30.4	59.6	0.6	4.8	8.1	12.0	17.7	30.1	59.6
	DURING	-2.0	4.2	7.3	10.5	15.0	24.5	46.2	-2.0	4.2	7.3	10.5	15.0	24.6	46.2
	AFTER	0.6	3.6	6.5	9.6	12.7	19.0	33.5	0.6	3.5	6.3	9.4	12.7	19.0	33.5
Queens	Overall	0.0	3.3	5.3	8.1	12.7	22.4	51.9	0.0	3.2	5.3	8.0	12.6	22.3	51.9
	BEFORE	1.6	3.7	6.1	9.7	15.8	27.2	51.9	1.6	3.6	6.0	9.4	15.6	26.3	51.9
	DURING	0.6	3.3	5.2	7.8	12.1	21.1	39.0	0.6	3.3	5.2	7.8	11.9	21.2	39.0
	AFTER	0.0	2.7	4.7	7.0	10.0	16.9	29.0	0.0	2.7	4.6	6.9	10.0	16.8	29.0
Rochester	Overall	-2.6	2	4.7	7.5	11.3	21.1	49.8	-2.6	2.0	4.6	7.4	11.1	20.7	49.8
	BEFORE	-2.1	2.3	5.3	8.7	13.8	27.3	49.8	-2.1	2.3	5.4	8.5	13.4	26.2	49.8
	DURING	-1.4	1.9	4.4	7.0	10.6	19.3	34.1	-1.4	1.9	4.3	7.0	10.5	19.1	34.1
	AFTER	-2.6	1.9	4.5	7.1	10.4	17.1	23.9	-2.6	1.9	4.3	6.7	10.0	16.7	23.9

NYS (Table 5), there were increased excess rates for all lag days for all three periods. They were significant for the BEFORE period, while for the DURING period, only the rates for lag days of 0–4, 0–5, and 0–6 were significant. For the AFTER period, only the lag day 0 value was significant. The interactions across periods were uniformly insignificant. There were also increased excess rates for all lag periods for asthma ED visits across all periods. However, an inverse pattern can be observed with generally insignificant increased rates in the BEFORE period, significant increases only for lag days ≥0–2, and significant increases for all lags in the AFTER period showing increasing excess rates across the periods. All of the *p*-values for period interactions were significant.

For COPD, the excess rates of ED visits were generally positive although there were several negative values during the BEFORE period (lags 0–2 and 0–3). However, all values were non-significant and the period interactions were also insignificant. All of the COPD hospitalization rates were positive, and there were significant increases for all lag days for both the BEFORE and AFTER periods. For the DURING period, only lag days 0–1 to 0–3 had significant excess rates. Except for lag day 0, the inter-period interactions were all significant.

Examination of the regional differences in excess rates (Table 6), shows patterns that are generally similar to the statewide values (Table 5). NYC generally represented the majority of cases except for COPD ED visits. The exceptions were COPD ED visits where none of the AFTER upstate rates were significant while the NYC values were and conversely, the BEFORE values for NYS were not significant, but the upstate values for lag days ≥0–3 were significant. Upstate asthma ED visits also had significant rate increases for lag days ≥0–3 where the statewide values were uniformly not significant. The inter-period interactions were significant for COPD hospitalizations, COPD ED visits, and asthma ED visits in NYC for most of the lag days.

Because of the possibility that these results were driven by patients with multiple hospitalizations or ED visits, the analyses were run again where only the first hospitalization or ED visit for each patient during the 2005 to 2016 period was included. For some of the patients, there could have been events prior to 2005, but we anticipate that these analyses substantially reduced the number of repeat cases. These results are presented in Supplementary Materials Tables S3–S5. Although the number of subjects in each category were reduced, the patterns of rates were very similar to those obtained for all of the ED visits and hospitalizations.

4. Discussion

These overall results for the excess rates of hospitalizations and ED visits for adult asthma and COPD associated with increased concentrations of $PM_{2.5}$ are comparable with previously reported values (Guarnieri and Balmes, 2014; Orellano et al., 2017; Li et al., 2016; Bloemsma et al., 2016). There are differences in these relative rates between the smaller upstate cities and NYC. For asthma, the rates in NYC are lower than for the upstate locations while for COPD, the direction

Table 3
Mean annual incidence rate (#/1000 persons per year) of hospital admissions and ED visits by period for asthma and COPD.

Outcome	Period	Overall	Albany	Bronx	Buffalo	Manhattan	Queens	Rochester
Hospitalization-asthma	BEFORE	1.67	0.95	2.67	0.78	1.65	1.33	0.79
	DURING	1.68	0.88	2.69	0.76	1.72	1.25	0.84
	AFTER	1.11	0.61	1.86	0.49	1.00	0.89	0.61
Hospitalization-COPD	BEFORE	1.29	2.42	1.19	1.60	1.13	1.24	1.36
	DURING	1.41	2.27	1.38	1.81	1.23	1.35	1.44
	AFTER	0.69	1.15	0.72	0.84	0.62	0.64	0.67
ED visit-asthma	BEFORE	5.48	3.82	9.71	3.15	5.18	3.38	2.68
	DURING	5.86	4.16	9.53	3.35	6.03	3.72	3.21
	AFTER	5.56	3.54	9.49	3.13	5.88	2.92	3.12
ED visit-COPD	BEFORE	0.35	1.08	0.32	0.82	0.22	0.18	0.60
	DURING	0.50	1.26	0.50	1.08	0.37	0.27	0.78
	AFTER	0.39	0.86	0.43	0.87	0.31	0.16	0.61

Table 4
Excess rates (%) of asthma and COPD hospital admissions and ED visits associated with each interquartile range (IQR) increase in $PM_{2.5}$ concentration by lag time and outcome.

Outcome	Lag (days)	IQR (μg/m^3)	N Cases	Excess rate (%) (95% C.I.)	p-value
Hospitalization-asthma	0	6.8	211,242	0.8 (0.1, 1.4)	0.016
	0–1	6.3	212,873	1.0 (0.3, 1.7)	0.004
	0–2	6.0	214,587	1.2 (0.5, 2.0)	< 0.001
	0–3	5.5	214,976	1.4 (0.7, 2.2)	< 0.001
	0–4	5.3	215,240	1.5 (0.8, 2.3)	< 0.001
	0–5	5.0	215,494	1.6 (0.8, 2.4)	< 0.001
	0–6	4.9	215,627	1.6 (0.8, 2.5)	< 0.001
Hospitalization-COPD	0	7.0	163,906	1.0 (0.2, 1.7)	0.009
	0–1	6.4	165,406	1.6 (0.8, 2.4)	< 0.001
	0–2	6.1	167,038	2.0 (1.2, 2.8)	< 0.001
	0–3	5.6	167,409	2.3 (1.4, 3.2)	< 0.001
	0–4	5.4	167,646	2.2 (1.3, 3.1)	< 0.001
	0–5	5.1	167,816	2.4 (1.4, 3.3)	< 0.001
	0–6	4.9	167,976	2.6 (1.7, 3.6)	< 0.001
ED Visit-asthma	0	6.8	783,927	0.6 (0.3, 0.9)	< 0.001
	0–1	6.2	790,409	0.7 (0.3, 1.0)	< 0.001
	0–2	5.9	797,057	0.8 (0.4, 1.1)	< 0.001
	0–3	5.4	798,427	0.8 (0.4, 1.2)	< 0.001
	0–4	5.1	799,542	0.9 (0.5, 1.3)	< 0.001
	0–5	4.9	800,431	1.1 (0.6, 1.5)	< 0.001
	0–6	4.7	801,004	1.4 (1.0, 1.8)	< 0.001
ED Visit-COPD	0	6.7	59,178	0.3 (−1.0, 1.5)	0.679
	0–1	6.2	59,832	0.8 (−0.6, 2.1)	0.262
	0–2	5.8	60,495	0.5 (−0.8, 1.9)	0.434
	0–3	5.4	60,614	0.7 (−0.7, 2.1)	0.354
	0–4	5.1	60,680	0.9 (−0.6, 2.3)	0.242
	0–5	5.0	60,732	1.1 (−0.5, 2.6)	0.169
	0–6	4.8	60,763	1.3 (−0.2, 3.0)	0.094

is reversed with NYC being higher. However, the differences are smaller than the associated confidence intervals and thus, there do not seem to be regional differences in the unit toxicity across NYS.

However, there is an apparent increase in toxicity per unit mass over time for COPD hospitalizations and asthma ED visits. Similar trends do not seem to occur for asthma hospitalizations or COPD ED visits. Over the period of 2005 to 2016, there were substantial decreases in the concentration of $PM_{2.5}$ and most of its major constituents (sulfate, nitrate, organic carbon, and elemental carbon) (Squizzato et al., 2018a). However, we have shown that in the AFTER period, there were increased concentrations of secondary organic carbon (SOC) which is formed through the oxidation of volatile organic compounds (VOCs) (Squizzato et al., 2018b; Zhang et al., 2018; Croft et al., 2019). SOC concentrations across NYS decreased between 2005 and 2007 and 2008–2013. However, small but significant increases in SOC concentrations during 2014–2016 were found at the ROC, ALB, BRO, and MAN sites (Masiol et al., 2019). The increases in SOC concentrations are likely the result of changes in gasoline composition between 2010 and 2014 (US EPA, 2017) and the increased propensity of the changed constituents to form SOC (Zhao et al., 2014, 2015, 2016), the increased use of gasoline direct injection engines (GDI) in light-duty vehicles (Zhao et al., 2018), and the increased number of registered vehicles in NYS from 2010 to 2016. When SOC is formed, it consists of significant amounts of peroxy radicals and peroxides (Docherty et al., 2005; Pagonis and Ziemann, 2018; Pavlovic and Hopke, 2010). These exogenous reactive oxygen species (ROS) in the $PM_{2.5}$ can then deliver a significant dose of oxidants to the respiratory system (Hopke, 2015) and potentially initiate adverse responses to the inhaled $PM_{2.5}$. Rich et al. (2019) examined the associations between source-specific $PM_{2.5}$ concentrations and the same cardiovascular diseases reported by Zhang et al. (2018). They found that spark-ignition and diesel vehicles, were associated with increased rates of cardiac arrhythmia and congestive heart failure hospitalizations over the next day, increased diesel $PM_{2.5}$ was associated with increased rates of congestive heart failure and ischemic heart disease hospitalizations over the next day, and increased acute cardiovascular hospitalization rates were associated with IQR increases in concentrations of road dust (RD), residual oil (RO), and secondary nitrate (SN) over the previous 1, 4, and 7 days. No other sources including road salt, sea salt, and secondary sulfate showed such associations.

Table 5
Excess rates (%) of asthma and COPD hospital admissions and emergency department visits associated with each interquartile range (IQR) increase in $PM_{2.5}$ concentration by lag time, outcome, and period (using common IQRs across the whole period).

			BEFORE		DURING		AFTER		
Outcome	Lag (days)	IQR (μg/m^3)	N cases	Excess rate (%) (95% C·I)	N cases	Excess rate (%) (95% C·I)	N cases	Excess rate (%) (95% C·I)	$PM_{2.5}$-period p-value
Hospitalization-asthma	0	6.8	57,636	0.9 (0.1, 1.8)	114,202	0.4 (−0.4, 1.3)	39,404	2.0 (0.2, 3.9)	0.244
	0–1	6.3	57,768	1.6 (0.6, 2.5)	115,546	0.3 (−0.6, 1.2)	39,559	1.9 (−0.0, 3.9)	0.081
	0–2	6.0	57,895	1.7 (0.7, 2.7)	116,979	0.7 (−0.2, 1.7)	39,713	1.9 (−0.2, 4.1)	0.259
	0–3	5.5	57,916	2.1 (1.0, 3.1)	117,315	0.9 (−0.1, 1.9)	39,745	1.7 (−0.5, 3.9)	0.218
	0–4	5.3	57,929	2.2 (1.1, 3.3)	117,526	1.1 (0.1, 2.1)	39,785	1.1 (−1.1, 3.3)	0.275
	0–5	5.0	57,929	2.1 (0.9, 3.2)	117,746	1.3 (0.2, 2.3)	39,819	1.2 (−1.0, 3.5)	0.548
	0–6	4.9	57,929	2.2 (1.0, 3.5)	117,857	1.3 (0.2, 2.4)	39,841	0.9 (−1.4, 3.3)	0.378
Hospitalization-COPD	0	7.0	44,060	1.1 (0.1, 2.2)	95,209	0.5 (−0.4, 1.5)	24,637	3.1 (0.7, 5.6)	0.119
	0–1	6.4	44,208	1.6 (0.5, 2.7)	96,486	1.1 (0.1, 2.1)	24,712	4.7 (2.1, 7.3)	0.035
	0–2	6.1	44,372	2.0 (0.9, 3.2)	97,866	1.4 (0.3, 2.5)	24,800	6.3 (3.5, 9.2)	0.005
	0–3	5.6	44,401	2.4 (1.2, 3.6)	98,179	1.6 (0.5, 2.7)	24,829	6.9 (3.9, 9.9)	0.003
	0–4	5.4	44,414	2.8 (1.5, 4.1)	98,382	1.1 (−0.0, 2.3)	24,850	7.4 (4.4, 10.6)	<0.001
	0–5	5.1	44,414	3.4 (2.1, 4.7)	98,539	0.8 (−0.3, 2.0)	24,863	8.1 (5.0, 11.3)	<0.001
	0–6	4.9	44,414	3.7 (2.3, 5.1)	98,680	1.0 (−0.2, 2.3)	24,882	8.7 (5.5, 12.1)	<0.001
ED Visit-asthma	0	6.8	189,260	0.4 (−0.1, 0.8)	397,485	0.3 (−0.2, 0.7)	197,182	2.7 (1.9, 3.5)	<0.001
	0–1	6.2	189,603	0.5 (0.0, 1.0)	402,724	0.3 (−0.1, 0.8)	198,082	2.6 (1.7, 3.5)	<0.001
	0–2	5.9	189,935	0.5 (−0.1, 1.0)	408,179	0.5 (0.0, 1.0)	198,943	2.7 (1.8, 3.6)	<0.001
	0–3	5.4	189,986	0.3 (−0.2, 0.9)	409,328	0.8 (0.3, 1.3)	199,113	2.2 (1.3, 3.2)	0.002
	0–4	5.1	190,027	0.3 (−0.3, 0.9)	410,235	1.1 (0.6, 1.7)	199,280	1.9 (0.9, 2.8)	0.007
	0–5	4.9	190,027	0.4 (−0.2, 1.0)	411,000	1.3 (0.8, 1.9)	199,404	1.9 (0.9, 2.9)	0.013
	0–6	4.7	190,027	0.7 (0.1, 1.4)	411,523	1.7 (1.1, 2.3)	199,454	2.1 (1.1, 3.2)	0.015
ED Visit-COPD	0	6.7	11,813	0.1 (−1.7, 2.0)	33,602	0.5 (−1.1, 2.1)	13,763	−0.2 (−3.1, 2.8)	0.911
	0–1	6.2	11,866	0.5 (−1.5, 2.5)	34,155	1.0 (−0.7, 2.7)	13,811	0.6 (−2.6, 4.0)	0.915
	0–2	5.8	11,920	−0.4 (−2.4, 1.7)	34,707	1.0 (−0.8, 2.7)	13,868	1.5 (−1.9, 5.0)	0.484
	0–3	5.4	11,925	−0.0 (−2.1, 2.1)	34,806	1.0 (−0.8, 2.8)	13,883	1.4 (−2.1, 4.9)	0.696
	0–4	5.1	11,930	0.3 (−1.8, 2.6)	34,859	1.0 (−0.9, 2.8)	13,891	2.1 (−1.5, 5.8)	0.701
	0–5	5.0	11,930	0.7 (−1.6, 3.1)	34,904	0.9 (−1.0, 2.9)	13,898	2.8 (−1.0, 6.7)	0.621
	0–6	4.8	11,930	1.4 (−1.1, 3.9)	34,934	1.0 (−1.0, 3.1)	13,899	2.8 (−1.1, 6.8)	0.704

Table 6
Excess rates of asthma and COPD hospital admissions and emergency department visits associated with each interquartile range (IQR) increase in $PM_{2.5}$ concentration by lag time, outcome, period, and region.

Outcome	Region	Lag (days)	IQR (μg/m^3)	BEFORE Cases	BEFORE Excess rate (%) (95% C·I)	DURING Cases	DURING Excess rate (%) (95% C·I)	AFTER Cases	AFTER Excess rate (%) (95% C·I)	p-value interaction across period
Hospitalization-asthma	NYC	0	8.1	52,483	0.9 (−0.2, 2.0)	103,896	0.2 (−0.8, 1.3)	35,803	1.9 (−0.4, 4.2)	0.320
		0–1	7.1	52,561	1.6 (0.4, 2.7)	105,078	0.1 (−0.9, 1.2)	35,932	2.0 (−0.3, 4.4)	0.082
		0–2	6.5	52,634	1.6 (0.4, 2.8)	106,355	0.6 (−0.5, 1.7)	36,064	2.1 (−0.3, 4.6)	0.281
		0–3	6.1	52,650	2.1 (0.8, 3.3)	106,677	0.8 (−0.3, 1.9)	36,096	1.9 (−0.6, 4.4)	0.257
		0–4	5.9	52,662	2.2 (0.9, 3.6)	106,884	1.1 (−0.1, 2.3)	36,136	1.1 (−1.5, 3.8)	0.390
		0–5	5.6	52,662	2.0 (0.6, 3.4)	107,102	1.4 (0.2, 2.6)	36,170	1.3 (−1.4, 3.9)	0.744
		0–6	5.3	52,662	2.2 (0.8, 3.6)	107,210	1.5 (0.2, 2.7)	36,192	1.0 (−1.7, 3.7)	0.626
	Upstate	0	6.8	5153	3.2 (0.2, 6.3)	10,306	3.7 (0.5, 7.0)	3601	6.9 (0.6, 13.6)	0.577
		0–1	6.3	5207	4.0 (0.8, 7.2)	10,468	3.6 (0.2, 7.0)	3627	4.2 (−2.4, 11.2)	0.978
		0–2	6	5261	4.2 (0.9, 7.7)	10,624	3.2 (−0.3, 6.8)	3649	1.6 (−5.2, 8.9)	0.762
		0–3	5.5	5266	4.0 (0.6, 7.4)	10,638	3.1 (−0.5, 6.8)	3649	0.8 (−6.0, 8.1)	0.715
		0–4	5.3	5267	4.4 (0.9, 7.9)	10,642	3.2 (−0.5, 7.0)	3649	1.2 (−5.7, 8.8)	0.708
		0–5	5	5267	4.3 (0.8, 8.0)	10,644	2.4 (−1.4, 6.3)	3649	1.1 (−6.1, 8.7)	0.620
		0–6	4.9	5267	4.3 (0.6, 8.1)	10,647	0.9 (−3.0, 4.9)	3649	−0.1 (−7.3, 7.7)	0.341
Hospitalization-COPD	NYC	0	8	33,298	1.6 (0.3, 3.0)	72,535	0.7 (−0.5, 2.0)	19,052	3.1 (0.0, 6.3)	0.271
		0–1	7.2	33,342	1.9 (0.5, 3.4)	73,440	1.2 (−0.1, 2.5)	19,110	5.1 (1.7, 8.6)	0.093
		0–2	6.7	33,394	2.0 (0.5, 3.5)	74,480	1.6 (0.2, 2.9)	19,179	6.8 (3.2, 10.6)	0.024
		0–3	6.1	33,409	2.1 (0.5, 3.7)	74,767	1.9 (0.6, 3.3)	19,208	7.9 (4.1, 11.8)	0.010
		0–4	5.9	33,417	2.3 (0.7, 4.0)	74,965	1.5 (0.1, 2.9)	19,229	8.7 (4.8, 12.8)	0.002
		0–5	5.5	33,417	2.9 (1.2, 4.6)	75,116	1.1 (−0.3, 2.5)	19,242	9.8 (5.8, 13.9)	<0.001
		0–6	5.2	33,417	3.0 (1.3, 4.8)	75,250	1.2 (−0.3, 2.6)	19,261	10.6 (6.6, 14.8)	<0.001
	Upstate	0	7	10,762	0.2 (−1.9, 2.4)	22,674	0.3 (−1.8, 2.5)	5585	4.5 (−0.5, 9.7)	0.268
		0–1	6.4	10,866	1.5 (−0.7, 3.7)	23,046	1.1 (−1.1, 3.4)	5602	4.9 (−0.4, 10.4)	0.418
		0–2	6.1	10,978	2.6 (0.3, 5.0)	23,386	1.3 (−1.0, 3.8)	5621	6.2 (0.6, 12.0)	0.255
		0–3	5.6	10,992	3.7 (1.4, 6.1)	23,412	1.0 (−1.4, 3.5)	5621	5.1 (−0.5, 11.0)	0.151
		0–4	5.4	10,997	4.6 (2.2, 7.1)	23,417	0.2 (−2.3, 2.8)	5621	5.1 (−0.7, 11.1)	0.020
		0–5	5.1	10,997	5.1 (2.6, 7.6)	23,423	0.1 (−2.4, 2.7)	5621	4.8 (−0.9, 10.9)	0.010
		0–6	4.9	10,997	5.8 (3.2, 8.4)	23,430	0.6 (−2.1, 3.3)	5621	4.6 (−1.3, 10.9)	0.013
ED Visits-asthma	NYC	0	7.8	169,476	0.4 (−0.2, 1.0)	353,467	0.4 (−0.1, 1.0)	176,361	3.4 (2.4, 4.4)	<0.001
		0–1	7	169,638	0.5 (−0.1, 1.1)	357,939	0.4 (−0.1, 1.0)	177,118	3.0 (2.0, 4.1)	<0.001
		0–2	6.4	169,781	0.4 (−0.3, 1.0)	362,625	0.6 (−0.0, 1.1)	177,849	3.1 (2.0, 4.1)	<0.001
		0–3	6	169,817	0.2 (−0.5, 0.8)	363,727	0.9 (0.3, 1.5)	178,019	2.4 (1.2, 3.5)	0.002
		0–4	5.8	169,852	−0.0 (−0.7, 0.7)	364,619	1.3 (0.7, 1.9)	178,186	1.8 (0.7, 3.0)	0.002
		0–5	5.5	169,852	0.1 (−0.7, 0.8)	365,375	1.6 (1.0, 2.3)	178,310	1.9 (0.7, 3.1)	0.001
		0–6	5.3	169,852	0.3 (−0.4, 1.1)	365,896	2.1 (1.5, 2.8)	178,360	2.2 (1.0, 3.4)	<0.001
	Upstate	0	6.8	19,784	0.1 (−1.3, 1.6)	44,018	−1.0 (−2.5, 0.5)	20,821	0.5 (−2.1, 3.1)	0.411
		0–1	6.2	19,965	1.0 (−0.5, 2.5)	44,785	−0.4 (−1.9, 1.2)	20,964	1.7 (−1.0, 4.5)	0.245
		0–2	5.9	20,154	1.5 (−0.1, 3.1)	45,554	0.4 (−1.2, 2.1)	21,094	1.9 (−1.0, 4.8)	0.522
		0–3	5.4	20,169	1.7 (0.1, 3.4)	45,601	0.6 (−1.0, 2.3)	21,094	2.9 (−0.0, 5.8)	0.323
		0–4	5.1	20,175	2.3 (0.6, 4.0)	45,616	0.8 (−0.9, 2.5)	21,094	3.2 (0.3, 6.2)	0.226
		0–5	4.9	20,175	3.0 (1.3, 4.8)	45,625	0.5 (−1.3, 2.3)	21,094	3.0 (−0.0, 6.1)	0.073
		0–6	4.7	20,175	3.7 (1.9, 5.5)	45,627	0.2 (−1.6, 2.0)	21,094	3.0 (−0.0, 6.2)	0.012
ED Visits-COPD	NYC	0	7.6	6762	0.1 (−2.5, 2.8)	20,734	0.6 (−1.6, 2.9)	8710	0.4 (−3.8, 4.8)	0.950
		0–1	6.8	6770	−0.3 (−3.1, 2.6)	21,063	0.9 (−1.4, 3.3)	8740	2.4 (−2.2, 7.2)	0.580
		0–2	6.2	6774	−2.6 (−5.4, 0.3)	21,431	1.0 (−1.4, 3.3)	8771	5.4 (0.6, 10.5)	0.010
		0–3	5.7	6774	−3.2 (−6.1, −0.2)	21,519	0.8 (−1.6, 3.2)	8786	5.4 (0.4, 10.6)	0.006
		0–4	5.4	6775	−3.1 (−6.2, 0.0)	21,565	0.7 (−1.7, 3.2)	8794	6.4 (1.2, 11.8)	0.004
		0–5	5.2	6775	−2.6 (−5.8, 0.7)	21,606	0.6 (−1.9, 3.2)	8801	6.9 (1.6, 12.5)	0.008
		0–6	4.9	6775	−1.3 (−4.6, 2.2)	21,635	0.7 (−1.8, 3.4)	8802	6.9 (1.5, 12.6)	0.034
	Upstate	0	6.7	5051	0.3 (−2.5, 3.2)	12,868	0.4 (−2.3, 3.1)	5053	−0.7 (−5.4, 4.3)	0.926
		0–1	6.2	5096	1.6 (−1.4, 4.7)	13,092	1.4 (−1.5, 4.4)	5071	−1.0 (−6.0, 4.3)	0.669
		0–2	5.8	5146	2.3 (−0.9, 5.5)	13,276	1.1 (−1.9, 4.1)	5097	−2.9 (−8.0, 2.4)	0.231
		0–3	5.4	5151	3.8 (0.6, 7.1)	13,287	1.2 (−1.8, 4.4)	5097	−3.2 (−8.4, 2.2)	0.066
		0–4	5.1	5155	4.4 (1.1, 7.8)	13,294	1.3 (−1.9, 4.5)	5097	−2.5 (−7.8, 3.0)	0.072
		0–5	5	5155	4.6 (1.1, 8.2)	13,298	1.4 (−2.0, 4.8)	5097	−1.5 (−7.0, 4.4)	0.140
		0–6	4.8	5155	4.7 (1.0, 8.4)	13,299	1.2 (−2.2, 4.8)	5097	−1.2 (−6.9, 4.8)	0.161

In the AFTER period, for patients hospitalized for COPD exacerbations, the largest effect estimates were observed for increased concentrations of $PM_{2.5}$ in the previous 4–7 days, but not sooner. However, for asthma, the largest relative rate estimates were observed for increases in $PM_{2.5}$ concentration in the 1–3 days prior to ED visits. This pattern is consistent with the different response of asthma and COPD to infection. Patients with asthma exacerbated by increases in $PM_{2.5}$ will likely suffer from a rapid onset of symptoms and present for medical care to address the typical dramatic symptoms of bronchial hyperreactivity leading to wheezing and dyspnea. This is supported by dyspnea being the most common comorbidity observed for ED visits for asthma, although it only represented 13% of the cases. It is possible that due to this earlier presentation, these patients with asthma were successfully treated in the ED and released without requiring hospitalization. Though patients with COPD can also present acutely over the next 1–4 days, they will likely have a slower onset of symptoms related to acute increases in $PM_{2.5}$ compared to patients with asthma. Typically, patients with COPD at baseline have more severe fixed obstruction and fewer reactive airway symptoms compared to patients with asthma, resulting in increased time to presentation (5–7 days). The more severe obstruction at baseline and thus less pulmonary reserve, as well as a much smaller degree of reversibility, in all likelihood accounts for the largest excess relative rates of hospitalization for COPD at the later lag times. Furthermore the older age and higher burden of cardiac comorbidities within our COPD population increases the likelihood of these patients being hospitalized. Our results are consistent with prior studies showing increased relative risks of ED visits and hospitalizations for obstructive lung disease (Halonen et al., 2008; Krall et al., 2017).

The strengths of this study include a large number of cases covering a relatively wide geographical area (New York State). One weakness of our study is that the study subjects assigned to any given site were assumed to be exposed to the same $PM_{2.5}$ concentrations for each specific day, regardless of the distance from that monitoring site. This approach likely resulted in some exposure misclassification and the resulting error would likely be a combination of Berkson and classical error, resulting in a bias toward the null and underestimation of the health effect (Zeger et al., 2000; Bateson et al., 2007). The observed differences in period specific rate ratios may result from the differences in the extent of exposure misclassification and underestimation by period (i.e. if the ambient $PM_{2.5}$ concentration was a better proxy for the individual subjects' $PM_{2.5}$ exposure in the AFTER period than in the DURING period, there would be a larger underestimation in the DURING period). Similar patterns were not observed for all of the outcomes, suggesting that this limitation only produces small effects. Future analyses would be required to investigate this possibility. Another potential concern is that the diagnosis classification codes changed on October 1, 2015, from the 9th version of the international classification of disease (ICD-9) to the 10th version (ICD-10). However, all ICD9 and ICD10 codes were reviewed by study physicians to ensure consistency of disease groups included and excluded from the study. Therefore, any outcome misclassification and downward bias should be minimal. Finally, a standard case crossover analysis was performed, and was therefore limited to 7-day lag periods to minimize the degree of overlap between case and control periods.

5. Conclusions

As we have observed with cardiovascular and respiratory infection hospitalizations and ED visits (Zhang et al., 2018; Croft et al., 2019), the overall rates of hospitalizations and ED visits for adult asthma and COPD have declined over the period of 2005 to 2016 as has the concentration of $PM_{2.5}$ across NYS. However the rate of COPD hospitalizations and ED visits for asthma per study period IQR increase in $PM_{2.5}$ concentration have increased in the later years (2014–2016) compared to earlier periods. Thus, measures that have been implemented to reduce the public's exposure to $PM_{2.5}$ as well as changes in the electricity generation driven by economics have resulted in significantly lower concentrations at all of the urban sites in NYS (Squizzato et al., 2018a). However, changes in composition have occurred in the form of increased concentrations of secondary organic carbon (Masiol et al., 2019). During the time that SOC has increased, there has also been increased toxicity per unit mass of the $PM_{2.5}$ with respect to hospitalizations for COPD and ED visits for adult asthma while the rate ratios for asthma hospitalization and COPD ED visits have not changed.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.04.357.

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