



Triggering of cardiovascular hospital admissions by source specific fine particle concentrations in urban centers of New York State



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ABSTRACT

Background: Previous work reported increased rates of acute cardiovascular hospitalizations associated with increased PM_{2.5} concentrations in the previous few days across urban centers in New York State from 2005 to 2016. These relative rates were higher after air quality policies and economic changes resulted in decreased PM_{2.5} concentrations and changes in PM composition (e.g. increased secondary organic carbon), compared to before and during these changes. Changes in PM composition and sources may explain this difference.

Objectives: To estimate the rate of acute cardiovascular hospitalizations associated with increases in source specific PM_{2.5} concentrations.

Methods: Using source apportioned PM_{2.5} concentrations at the same NYS urban sites, a time-stratified case-crossover design, and conditional logistic regression models adjusting for ambient temperature and relative humidity, we estimated the rate of these acute cardiovascular hospitalizations associated with increases in mean source specific PM_{2.5} concentrations in the previous 1, 4, and 7 days.

Results: Interquartile range (IQR) increases in spark-ignition emissions (GAS) concentrations were associated with increased excess rates of cardiac arrhythmia hospitalizations (2.3%; 95% CI = 0.4%, 4.2%; IQR = 2.56 μg/m³) and ischemic stroke hospitalizations (3.7%; 95% CI = 1.1%, 6.4%; 2.73 μg/m³) over the next day. IQR increases in diesel (DIE) concentrations were associated with increased rates of congestive heart failure hospitalizations (0.7%; 95% CI = 0.2%–1.3%; 0.51 μg/m³) and ischemic heart disease hospitalizations (0.8%; 95% CI = 0.3%, 1.3%; 0.60 μg/m³) over the next day, as hypothesized. However, secondary sulfate PM_{2.5} (SS) was not. Increased acute cardiovascular hospitalization rates were also 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, but not other sources.

Conclusions: These findings suggest a role of several sources of PM_{2.5} in New York State (i.e. traffic emissions, non-traffic emissions such as brake and tire wear, residual oil, and nitrate that may also reflect traffic emissions) in the triggering of acute cardiovascular events.

1. Introduction

We and others have reported that short term increases in ambient fine particle concentrations were associated with triggering of acute

cardiovascular and cerebrovascular events (Brook et al., 2004; Brook et al., 2010; Rajagopalan et al., 2018), including myocardial infarction (Evans et al., 2017; Gardner et al., 2014; Mustafic et al., 2012; Pope et al., 2015), ischemic stroke (Shah et al., 2015), cardiac arrhythmia

Abbreviations: GAS, spark ignition emissions; DIE, diesel; SN, secondary nitrate; SS, secondary sulfate; RD, road dust; RO, residual oil; AGS, aged sea salt; FSS, fresh sea salt; IND, industry; BB, biomass burning; OP, pyrolyzed organic rich; RS, road salt

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(Link et al., 2013; Rich et al., 2005; Rich et al., 2006a; Rich et al., 2006b), and heart failure (Shah et al., 2013). Recently, we found that short-term increases in ambient PM_{2.5} concentrations were associated with small but significant increases in the rate of hospital admissions for cardiac arrhythmia, ischemic stroke, congestive heart failure, ischemic heart disease, and myocardial infarction across urban centers of New York State from 2005 to 2016 (Zhang et al., 2018). We also reported that implementation of air quality policies and economic changes occurring from 2008 to 2013 led to reductions of pollutant emissions and concentrations of PM_{2.5} and its major constituents (sulfate, nitrate, elemental carbon and organic carbon) as well as gaseous pollutants (NO₂, SO₂, and CO) except ozone. Further, there were increased concentrations of secondary organic carbon concentrations, but decreases in secondary inorganic species (sulfate and nitrate) and primary organic carbon concentrations (Squizzato et al., 2018a; Zhang et al., 2018). Although there were no differences in the relative rate for most disease subgroups Before (2005–2007), During (2008–2013), or After (2014–2016) these pollutant changes, the rate of hospital admissions for ischemic heart disease associated with increased PM_{2.5} concentration was higher in the After period (Zhang et al., 2018). This result suggests that changes in particle composition resulting from these policies and the co-occurring economic drivers may have differentially triggered these acute cardiovascular outcomes.

Specific PM_{2.5} sources emit particles with chemical fingerprints (profiles) that permit source identification and apportionment. Source apportionment analyses have been conducted in numerous regions and cities around the world (Belis et al., 2013; Hopke, 2016a, 2016b), and have been used to examine whether PM sources were individually associated with health events (Ebisu et al., 2018; Halonen et al., 2009; Ito et al., 2006; Krall et al., 2018; Laden et al., 2000; Mar et al., 2000; Mar et al., 2006; Ozkaynak and Thurston, 1987; Thurston et al., 2005). Using positive matrix factorization (PMF) to apportion the measured mass of an atmospheric pollutant at a given site to potential emission sources by solving a mass balance equation (Hopke, 2016a), we separately identified twelve PM_{2.5} sources at six urban sites (Buffalo, Rochester, Albany, Bronx, Manhattan, Queens) and 2 background sites in New York State (Whiteface Mountain and Pinnacle State Park) (Squizzato et al., 2018b). There were 7 PM_{2.5} sources common to all sites (secondary sulfate [SS], secondary nitrate [SN], biomass burning [BB], diesel [DIE], spark-ignition emissions [GAS], pyrolyzed organic rich [OP], road dust [RD]), 3 sources identified at New York City sites only (Bronx, Manhattan, Queens)(Aged sea salt [AGS], fresh sea salt [FSS], residual oil [RO]), 1 source identified in Buffalo, Rochester, and Albany only (road salt [RS]), and 1 source identified at Buffalo only (industrial [IND]). The primarily transported secondary aerosols (SS, SN, and OP) were observed at all sites since their contributions were driven by regionally distributed sources. Ubiquitous sources such as the three traffic sources (DIE, GAS, and RD) were also observed at all sites. Biomass burning was also seen at all sites due to the common practice of recreational wood burning in wood stoves and fireplaces during the winter months, occasional summer wildfire plumes, and an increasing summer use of outdoor fire pits (Zhang et al., 2018). Given the colder and snowier conditions, road salt was identified at all the upstate sites. New York City had residual oil that had been extensively used for large building space heating, and sea salt sources that were not observed elsewhere. For the “industrial” source identified in Buffalo, we could not attribute this factor to any specific activity (Squizzato et al., 2018b). We also reported that increased spark-ignition vehicle emissions were consistent with increased vehicle registrations in New York, and that increased SOC was consistent with projected increases in its formation due to reduced NO_x emissions in New York State. Our previous work has also suggested higher risks/rates of myocardial infarction associated with PM_{2.5} when the air pollution mixture is enhanced with secondary particles, ammonium sulfate, and ammonium nitrate (Hopke et al., 2015; Rich et al., 2013), while increased mortality rates were associated with increased secondary sulfate concentrations (Ito et al.,

2006).

Therefore, using the same New York State hospitalization dataset (2005–2016) as in our previous analyses (Zhang et al., 2018), and these PM_{2.5} sources from the six urban NYS sites (Squizzato et al., 2018b), we estimated the rates of acute cardiovascular event hospitalizations (cardiac arrhythmia, ischemic stroke, congestive heart failure, ischemic stroke, and myocardial infarction) associated with increases in the mean contributions of individual PM_{2.5} sources over the previous 1, 4, and 7 days. We hypothesized that increased motor vehicle emissions (diesel PM_{2.5} [DIE] and spark-ignition emissions PM_{2.5} [GAS]) as well as secondary sulfate PM_{2.5} (SS) would be associated with increased rates of hospitalizations for these acute cardiovascular events.

2. Materials and methods

2.1. Study population and hospital admissions data

The hospital admissions used in the study have been described previously (Zhang et al., 2018). Briefly, we retained hospital admissions from the New York State Department of Health Statewide Planning and Research Cooperative System (SPARCS), a legislatively mandated database that covers ~95% of hospitals in NYS, excluding federal facilities (e.g. Veterans Affairs Hospitals) and psychiatric facilities. It contains billing and medical information on over 2.5 million discharges for New York State hospitals per year. SPARCS data include patient information on the principal diagnoses and up to 24 other diagnoses at the time of hospital admission, as well as demographic characteristics and event/hospital information. We geocoded the residential address for each hospitalization using ArcGIS 10.3.1 (©Esri, Inc. Redlands, CA). Annual geocoding success rates from 2015 to 2016 ranged from 95.0% to 95.9%. We retained those hospital admissions with a successfully geocoded address, a “principal” diagnoses of cardiovascular disease (defined using ICD-9 and ICD-10 codes), and an admission date from January 1, 2005 to December 31, 2016, for adult (≥ 18 years of age) residents of NYS. We then used this principal diagnosis to define cardiac arrhythmias (ICD-9 = 427 and ICD-10 = I47-I49), congestive heart failure (ICD-9 = 428 and ICD-10 = I42 and I50-I51), ischemic heart disease (ICD-9 = 410–414 and ICD-10 = I20-I25), myocardial infarction (ICD-9 = 410 and ICD-10 = I21), and ischemic stroke (ICD-9 = 434 and ICD-10 = I63). We then excluded all study subjects living > 15 miles from any our six PM_{2.5} monitoring sites, leaving *N* = 1,802,836 available for analysis. This study was reviewed and approved by the Institutional Review Board at the State University of New York at Albany.

2.2. PM_{2.5} composition and weather data

PM_{2.5} compositional data were retrieved from the EPA Chemical Speciation Network (CSN; AQS, www.epa.gov/aqs), for six sites (Albany, Buffalo, Rochester, Bronx, Manhattan, and Queens). Daily (24 h) samples were collected every third or sixth day and analyzed for species that would provide mass closure. Elemental carbon (EC) and organic carbon (OC) were determined by thermo-optical analysis, major inorganic ions by ion chromatography, and elements by energy-dispersive X-ray fluorescence. Details of the sampling methods, analytical protocols, and quality assurance/quality control are summarized in Solomon et al. (Solomon et al., 2014).

Positive matrix factorization (PMF) (Hopke, 2016a), using U.S. EPA PMF version 5, was used to identify PM_{2.5} sources at each site (Squizzato et al., 2018b). PMF protocols were in compliance with guidelines and best practices reported in the literature (e.g. (Belis et al., 2014; Brown et al., 2015; Masiol et al., 2017; Paatero et al., 2014)). The best solutions were identified according to several criteria and guidelines (Belis et al., 2014; Brown et al., 2015; Hopke, 2016a; Reff et al., 2007): (i) knowledge of sources affecting the study area, (ii) the *Q*-value with respect to the expected (theoretical) value and its stability over

multiple runs ($n = 200$), (iii) number of absolute scaled residuals greater than ± 3 , and (iv) finding profile uncertainties calculated by bootstrap (BS, $n = 200$) and displacement (DISP) methods within an acceptable range (Paatero et al., 2014). Further details of methods for data handling, source apportionment analysis as well as all the source profiles and the basis of their interpretation are extensively discussed in Squizzato et al. (2018b). The trends in the apportioned source contributions are presented in Masiol et al. (2019). The twelve $PM_{2.5}$ sources identified were then used in the statistical analyses described below.

Hourly temperature and relative humidity data were obtained from the National Weather Service (National Climate Data Center, <https://www.ncdc.noaa.gov/cdo-web/datatools/lcd>) for the nearest major airport (BUF - Buffalo, ROC - Rochester, ALB - Albany, LGA - Bronx, and JFK - Queens) or the closest weather station (Central Park for Manhattan). For each study subject living within 15 miles of our six monitoring stations, we assigned $PM_{2.5}$ source contributions, temperature, and relative humidity measurements from the nearest site. If a person lived < 15 miles from more than one monitor (e.g. Bronx vs. Manhattan), we assigned concentrations/values from the closest monitor to that person.

2.3. Study design and statistical analyses

To estimate the relative rate of cardiac arrhythmia associated with short term increases in $PM_{2.5}$ source contributions (e.g. DIE), we used the same time-stratified, case-crossover design and conditional logistic regression analyses (Levy et al., 2001; Maclure, 1991) used in our previous analysis of $PM_{2.5}$ and acute cardiovascular hospitalizations (Zhang et al., 2018). The case-crossover design contrasts pollutant concentrations immediately before the cardiovascular disease admission (case periods) to other times when the subject did not have a cardiovascular disease admission (control periods), matched to the case period (3–4 controls per case) by calendar month and weekday. Although factors such as gender, race, and health history are the same for the case and control period (i.e. same person for both periods), other variables such as temperature and relative humidity are not constant across the time periods and thus must be included in the analytic models. We fit a conditional logistic regression model for cardiac arrhythmia hospitalizations and each $PM_{2.5}$ source described above, in which we regressed case–control status (i.e., case = 1, control = 0) against the mean $PM_{2.5}$ source concentration, mean $rPM_{2.5}$ concentration (i.e. residual $PM_{2.5} = PM_{2.5}$ mass – specific $PM_{2.5}$ source mass), an indicator variable for holidays, and temperature and relative humidity (each with a natural spline with 4 degrees of freedom determined using Akaike's Information Criterion), on the case and control days (all variables on lag day 0). As is standard in case-crossover studies, this model provided estimates of the rate ratio and its 95% confidence interval. The excess rate is the percent (%) increase in the rate per interquartile range increase in source specific $PM_{2.5}$ concentration (i.e. $[\text{rate ratio} - 1.0] * 100\%$). We then re-ran this set of models for each $PM_{2.5}$ source for lag days 0–3 and then lag days 0–6, and then again for each outcome (congestive heart failure, ischemic heart disease, myocardial infarction, and ischemic stroke). Since there were 3 lagged effects estimated for each outcome/ $PM_{2.5}$ source, a $p < 0.017$ was used to define statistical significance. In exploratory analyses, we then re-ran this model with interaction terms between period (Before, During, and After) and $PM_{2.5}$. All data management and statistical analyses were done using R version 3.0.1 (<https://www.r-project.org/>).

3. Results

Since some of the PMF sources identified by Squizzato et al. (2018b) were identified at all sites, but others were only identified in New York City, upstate sites (Buffalo, Rochester, Albany), or just in Buffalo, a description of the study population for each site group is shown in

Table 1. Across all sites, study subjects were predominantly female (54.2%), white (52.2%), and non-Hispanic (89.6%), with a mean (\pm standard deviation) age of 69 (± 15) years, and a mean (\pm standard deviation) hospital length of stay of 5.05 (± 7.39) days with generally larger proportions of hospitalizations at the beginning of the study period than near the end. The four site groups had similar mean length of stays, and similar age, season of admission, and year of admission distributions. However, the Upstate sites and Buffalo had substantially larger percentages of white subjects (81.0% and 82.4%, respectively) than the New York City sites and All sites (46.6% and 52.2%, respectively), and substantially smaller percentages of Hispanic subjects (2.8% and 1.3%, respectively) than the New York City sites and All sites (12.0% and 10.4%, respectively).

The distributions of source specific $PM_{2.5}$ contributions are shown in **Table 2**. Detailed descriptions of each source and their chemical profiles are provided in Squizzato et al. (2018b), while the trends in the apportioned source contributions are presented in Masiol et al. (2019). The excess rates of hospitalizations for cardiac arrhythmia, ischemic stroke, congestive heart failure, ischemic heart disease, and myocardial infarction associated with increased contribution of each $PM_{2.5}$ source on the same day (lag day 0), previous 4 days (lag days 0–3), and previous 7 days (lag days 0–6) are shown in **Table 3** and **Fig. 1**. As hypothesized, we generally observed increased excess rates of hospitalizations associated with increased DIE and GAS contributions. Each interquartile range (IQR) increase in GAS contributions on the same day was associated with a 3.5% increase in the rate of ischemic stroke hospitalization (95% CI = 1.0%, 6.0%) and a 2.2% excess rate of cardiac arrhythmia hospitalization (95% CI = 0.4%, 4.1%). Although not statistically significant, most excess rates of cardiac arrhythmia, ischemic stroke, congestive heart failure, and myocardial infarction associated with increased GAS contributions on the same day and previous 4 and 7 days were also positive (i.e. $> 0.0\%$). Interquartile range increases in DIE contributions on the same day were also associated with increased excess rates of congestive heart failure (0.7%; 95% CI = 0.2%, 1.3%; IQR = $0.53 \mu\text{g}/\text{m}^3$) and ischemic heart disease (0.6%; 95% CI = 0.1%, 1.1%; IQR = $0.53 \mu\text{g}/\text{m}^3$) hospital admissions. However, interquartile range increases in SS contributions were generally not associated with an increased rate of hospitalization for any outcome. In fact, each $1.65 \mu\text{g}/\text{m}^3$ increase in SS contribution in the previous 7 days was associated with a -1.4% decreased excess rate of cardiac arrhythmia (95% CI = -2.5% , -0.3%).

Increased contributions of other $PM_{2.5}$ sources (RD, SN, and RO) were also generally associated with increased rates of cardiovascular hospitalizations (**Fig. 1**, **Table 3**). For example, interquartile range increases in RD contribution on the same day were associated with significantly increased excess rates of ischemic heart disease hospitalizations (0.6%; 95% CI = 0.1%, 1.1%; IQR = $0.30 \mu\text{g}/\text{m}^3$). Although not statistically significant, most excess rates of congestive heart failure, ischemic heart disease, and myocardial infarction associated with increased RD contributions on the same day and previous 4 and 7 days were positive. Each interquartile range increase in SN contribution over the previous 4 days was associated with an increased excess rate of myocardial infarction (1.7%; 95% CI = 0.4%, 3.0%; IQR = $1.53 \mu\text{g}/\text{m}^3$). Again, although not statistically significant, most excess rates of congestive heart failure, ischemic heart disease, and myocardial infarction associated with increased SN contributions on the same day and previous 4 and 7 days were positive. Each $0.63 \mu\text{g}/\text{m}^3$ increase in RO contribution was associated with an increased excess rate of ischemic heart disease (1.8%, 95% CI = 0.4%, 3.1%) over the next 4 days, with most other excess rates also positive.

In contrast, there were no clear patterns of association between increased AGS or FSS contributions and rates of any outcome, while for other $PM_{2.5}$ sources (OP, RS, IND, BB, OP), there were mixed results (**Table 3**). For example, although each IQR increase in RS contribution in the previous 4 days was associated with an increased excess rate of ischemic stroke (2.5%, 95% CI = 0.6%, 4.4%, IQR = $0.08 \mu\text{g}/\text{m}^3$), most

Table 1
Subject and hospital admission characteristics, by site group.

	All sites (N = 1,802,836)		New York City sites only (N = 1,468,801)		Buffalo, Rochester, Albany only (N = 334,035)		Buffalo only (N = 151,684)	
	n	%	n	%	n	%	n	%
DISEASE								
Cardiac arrhythmia	321,342	22.9	259,535	22.5	61,807	25.1	27,022	24.5
Ischemic stroke	173,587	12.4	135,530	11.7	38,057	15.5	17,411	15.8
Congestive heart failure	448,222	32.0	362,788	31.4	85,434	34.7	36,389	33.0
Ischemic heart disease	631,193	45.1	532,520	46.1	98,673	40.1	46,989	42.6
Myocardial infarction	228,492	16.3	178,428	15.5	50,064	20.4	23,873	21.6
GENDER								
Male	640,977	45.8	525,790	45.5	115,187	46.8	53,080	48.1
AGE								
Years: Mean (standard deviation)	69.27 (14.56)		68.86 (14.53)		71.18 (14.55)		71.24 (14.46)	
18–39	34,727	2.5	29,661	2.6	5066	2.1	2260	2.1
40–49	99,861	7.1	84,968	7.4	14,893	6.1	6582	6.0
50–59	229,529	16.4	193,631	16.8	35,898	14.6	15,880	14.4
60–69	311,812	22.3	263,278	22.8	48,534	19.7	21,375	19.4
70–79	333,000	23.8	275,520	23.9	57,480	23.4	26,554	24.1
≥ 80	391,828	28.0	307,785	26.7	84,043	34.2	37,749	34.2
RACE								
White	731,723	52.2	532,662	46.1	199,061	81.0	91,014	82.4
African American	315,831	22.6	285,547	24.7	30,284	12.3	14,484	13.1
Native American or Alaskan Native	7631	0.5	7338	0.6	293	0.1	162	0.2
Asian	42,676	3.1	41,917	3.6	759	0.3	262	0.2
Native Hawaiian or Pacific Islander	454	0.0	392	0.0	62	0.0	8	0.0
ETHNICITY								
Hispanic	145,358	10.4	138,542	12.0	6816	2.8	1420	1.3
YEAR OF ADMISSION								
2005	141,846	10.1	116,679	10.1	25,167	10.2	11,267	10.2
2006	140,095	10.0	115,657	10.0	24,438	9.9	10,862	9.8
2007	133,093	9.5	109,797	9.5	23,296	9.5	10,308	9.3
2008	131,712	9.4	108,622	9.4	23,090	9.4	10,625	9.6
2009	129,512	9.3	107,280	9.3	22,232	9.0	9967	9.0
2010	122,615	8.8	101,875	8.8	20,740	8.4	9418	8.5
2011	112,586	8.0	93,136	8.1	19,450	7.9	8646	7.8
2012	107,317	7.7	88,872	7.7	18,445	7.5	8287	7.5
2013	102,399	7.3	84,676	7.3	17,723	7.2	8192	7.4
2014	95,730	6.8	78,471	6.8	17,259	7.0	7958	7.2
2015	95,406	6.8	78,135	6.8	17,271	7.0	7754	7.0
2016	88,446	6.3	71,643	6.2	16,803	6.8	7116	6.5
SEASON OF ADMISSION								
Fall	339,652	24.3	280,212	24.3	59,440	24.2	26,675	24.2
Spring	370,866	26.5	306,325	26.5	64,541	26.3	28,892	26.2
Summer	340,972	24.3	281,217	24.4	59,755	24.3	26,936	24.4
Winter	349,267	24.9	287,089	24.9	62,178	25.3	27,897	25.3
LENGTH OF HOSPITAL STAY (DAYS)								
Mean (standard deviation)	5.05 (7.39)		5.07 (7.21)		4.98 (8.17)		5.05 (7.13)	

Table 2
Distribution of daily PM_{2.5} source concentrations (µg/m³) for control periods.

PM _{2.5} source	Mean	Standard deviation	Minimum	5th %tile	25th %tile	50th %tile	75th %tile	95th %tile	Maximum
All sites									
Road Dust (RD)	0.45	0.52	−0.20	0.00	0.14	0.30	0.58	1.39	6.39
Secondary Sulfate (SS)	3.12	3.93	−0.94	−0.38	0.76	2.04	4.09	10.50	42.47
Secondary Nitrate (SN)	1.81	2.80	−0.78	−0.16	0.13	0.75	2.37	7.65	24.12
Diesel (DIE)	1.09	0.89	−0.38	0.09	0.53	0.92	1.44	2.67	10.26
Spark-Ignition Emissions (GAS)	1.60	1.67	−0.44	−0.17	0.41	1.13	2.32	4.92	14.60
Biomass Burning (BB)	0.37	0.53	−0.22	−0.05	0.04	0.18	0.53	1.38	9.92
Pyrolyzed Organic Rich (OP)	1.31	1.81	−0.34	−0.18	0.11	0.83	1.83	4.35	20.24
New York City sites only									
Fresh Sea Salt (FSS)	0.20	0.66	−0.08	−0.01	0.00	0.02	0.10	0.98	10.64
Aged Sea Salt (AGS)	0.60	0.74	−0.15	−0.03	0.10	0.37	0.80	2.08	7.93
Residual Oil (RO)	0.63	0.80	−0.20	−0.07	0.11	0.38	0.85	2.20	7.17
Buffalo, Rochester, and Albany only									
Road Salt (RS)	0.16	0.68	−0.10	−0.01	0.01	0.02	0.09	0.70	10.88
Buffalo only									
Industrial (IND)	0.20	0.21	−0.05	−0.03	0.06	0.15	0.25	0.64	1.26

Table 3
Excess rate of acute cardiovascular hospitalizations associated with each interquartile range increase in PM_{2.5} source contribution.

Outcome	Lag	Secondary Nitrate (SN)				Secondary Sulfate (SS)			
		N Cases	IQR (µg/m ³)	Excess Rate % (95% CI)	p-value	N Cases	IQR (µg/m ³)	Excess Rate % (95% CI)	p-value
Cardiac arrhythmia	0	63,582	1.18	0.1 (-0.5, 0.6)	0.821	63,582	2.21	-0.2 (-0.9, 0.5)	0.585
	0-3	44,582	1.53	-0.1 (-1.3, 1.0)	0.811	44,582	2.04	-0.5 (-1.5, 0.6)	0.404
	0-6	47,316	1.45	0.2 (-1.2, 1.6)	0.767	47,316	1.65	-1.4 (-2.5, -0.3)	0.010
Ischemic stroke	0	34,963	1.18	0.8 (0.1, 1.6)	0.027	34,963	2.21	-0.3 (-1.3, 0.6)	0.484
	0-3	24,682	1.53	-1.3 (-2.9, 0.2)	0.095	24,682	2.04	-0.2 (-1.7, 1.3)	0.813
	0-6	26,174	1.45	-0.7 (-2.5, 1.2)	0.490	26,174	1.65	-0.1 (-1.6, 1.4)	0.900
Congestive heart failure	0	90,546	1.18	0.2 (-0.3, 0.6)	0.478	90,546	2.21	0.4 (-0.2, 1.0)	0.192
	0-3	64,598	1.53	0.7 (-0.2, 1.6)	0.125	64,598	2.04	0.0 (-0.9, 0.9)	0.956
	0-6	67,626	1.45	0.1 (-0.9, 1.2)	0.832	67,626	1.65	-0.1 (-1.0, 0.8)	0.872
Ischemic heart disease	0	127,957	1.18	0.3 (0.0, 0.7)	0.081	127,957	2.21	-0.1 (-0.5, 0.4)	0.793
	0-3	90,443	1.53	0.8 (0.1, 1.6)	0.024	90,443	2.04	-0.1 (-0.8, 0.6)	0.743
	0-6	96,085	1.45	0.9 (0.0, 1.8)	0.048	96,085	1.65	-0.2 (-1.0, 0.5)	0.507
Myocardial infarction	0	45,794	1.18	0.5 (-0.1, 1.1)	0.135	45,794	2.21	-0.6 (-1.4, 0.2)	0.125
	0-3	31,991	1.53	1.7 (0.4, 3.0)	0.009	31,991	2.04	-0.2 (-1.4, 1.1)	0.779
	0-6	33,937	1.45	0.8 (-0.7, 2.3)	0.290	33,937	1.65	-0.4 (-1.7, 0.8)	0.512
Spark-Ignition Emissions (GAS)					Diesel (DIE)				
Outcome	Lag	N Cases	IQR (µg/m ³)	Excess Rate % (95% CI)	p-value	N Cases	IQR (µg/m ³)	Excess Rate % (95% CI)	p-value
Cardiac arrhythmia	0	63,582	2.56	2.2 (0.4, 4.1)	0.019	63,582	0.53	-0.2 (-0.9, 0.5)	0.547
	0-3	44,582	1.72	1.3 (-0.9, 3.4)	0.251	44,582	0.69	-1.1 (-2.7, 0.5)	0.174
	0-6	47,316	1.49	0.4 (-1.8, 2.6)	0.726	47,316	0.71	-0.6 (-2.6, 1.4)	0.571
Ischemic stroke	0	34,963	2.56	3.5 (1.0, 6.0)	0.005	34,963	0.53	0.0 (-1.0, 1.0)	0.971
	0-3	24,682	1.72	2.3 (-0.5, 5.2)	0.102	24,682	0.69	0.4 (-1.8, 2.7)	0.712
	0-6	26,174	1.49	1.1 (-1.7, 3.9)	0.459	26,174	0.71	1.5 (-1.3, 4.3)	0.296
Congestive heart failure	0	90,546	2.56	1.5 (-0.1, 3.0)	0.067	90,546	0.53	0.7 (0.2, 1.3)	0.013
	0-3	64,598	1.72	1.8 (0.0, 3.6)	0.050	64,598	0.69	0.0 (-1.3, 1.3)	0.992
	0-6	67,626	1.49	1.6 (-0.2, 3.5)	0.088	67,626	0.71	-1.0 (-2.6, 0.6)	0.230
Ischemic heart disease	0	127,957	2.56	0.5 (-0.8, 1.9)	0.461	127,957	0.53	0.6 (0.1, 1.1)	0.102
	0-3	90,443	1.72	0.0 (-1.6, 1.5)	0.953	90,443	0.69	-0.3 (-1.4, 0.7)	0.538
	0-6	96,085	1.49	0.0 (-1.6, 1.6)	0.953	96,085	0.71	0.7 (-0.7, 2.0)	0.333
Myocardial infarction	0	45,794	2.56	2.3 (0.1, 4.5)	0.039	45,794	0.53	0.4 (-0.5, 1.2)	0.393
	0-3	31,991	1.72	0.0 (-2.4, 2.6)	0.976	31,991	0.69	-0.7 (-2.5, 1.2)	0.497
	0-6	33,937	1.49	0.7 (-1.8, 3.3)	0.572	33,937	0.71	0.2 (-1.2, 2.5)	0.894
Road Dust (RD)					Biomass Burning (BB)				
Outcome	Lag	N Cases	IQR (µg/m ³)	Excess Rate % (95% CI)	p-value	N Cases	IQR (µg/m ³)	Excess Rate % (95% CI)	p-value
Cardiac arrhythmia	0	63,582	0.30	-0.3 (-1.0, 0.5)	0.506	63,582	0.59	-0.2 (-1.4, 1.0)	0.716
	0-3	44,582	0.21	0.0 (-0.9, 0.9)	0.997	44,582	0.42	0.2 (-1.4, 1.8)	0.773
	0-6	47,316	0.24	-0.2 (-1.4, 1.0)	0.740	47,316	0.36	0.0 (-1.6, 1.7)	0.966
Ischemic stroke	0	34,963	0.30	0.3 (-0.7, 1.3)	0.585	34,963	0.59	1.7 (0.0, 3.3)	0.046
	0-3	24,682	0.21	-0.4 (-1.5, 0.8)	0.524	24,682	0.42	1.3 (-0.9, 3.6)	0.257
	0-6	26,174	0.24	-0.5 (-2.0, 1.1)	0.265	26,174	0.36	0.4 (-0.8, 2.6)	0.747
Congestive heart failure	0	90,546	0.30	0.5 (-0.2, 1.1)	0.147	90,546	0.59	0.5 (-0.4, 1.5)	0.278
	0-3	64,598	0.21	-0.1 (-0.8, 0.6)	0.747	64,598	0.42	1.4 (0.1, 2.7)	0.040
	0-6	67,626	0.24	0.3 (-0.7, 1.3)	0.539	67,626	0.36	0.9 (-0.4, 2.3)	0.175
Ischemic heart disease	0	127,957	0.30	0.6 (0.1, 1.1)	0.015	127,957	0.59	-0.8 (-1.6, 0.0)	0.057
	0-3	90,443	0.21	0.5 (-0.1, 1.1)	0.085	90,443	0.42	-0.3 (-1.3, 0.7)	0.570
	0-6	96,085	0.24	0.3 (-0.5, 1.0)	0.533	96,085	0.36	0.4 (-0.6, 1.5)	0.416
Myocardial infarction	0	45,794	0.30	0.8 (0.0, 1.7)	0.058	45,794	0.59	0.8 (-0.6, 2.1)	0.269
	0-3	31,991	0.21	0.1 (-0.8, 1.8)	0.904	31,991	0.42	0.4 (-1.4, 2.2)	0.672
	0-6	33,937	0.24	0.8 (-0.6, 2.2)	0.280	33,937	0.36	0.8 (-1.0, 2.6)	0.405
Pyrolyzed Organic Rich (OP)					Fresh Sea Salt (FSS)				
Outcome	Lag	N Cases	IQR (µg/m ³)	Excess Rate % (95% CI)	p-value	N Cases	IQR (µg/m ³)	Excess Rate % (95% CI)	p-value
Cardiac arrhythmia	0	43,429	1.54	0.4 (-0.8, 1.7)	0.513	53,931	0.09	0.1 (-0.0, 0.3)	0.168
	0-3	30,180	0.96	1.1 (-0.2, 2.5)	0.085	40,634	0.14	0.1 (-0.3, 0.5)	0.552
	0-6	32,479	0.93	1.6 (-0.0, 3.3)	0.022	40,698	0.15	0.4 (-0.2, 0.9)	0.234
Ischemic stroke	0	25,074	1.54	-1.0 (-2.6, 0.8)	0.272	29,014	0.09	0.3 (0.0, 0.5)	0.024
	0-3	17,606	0.96	0.8 (-1.0, 2.6)	0.376	22,309	0.14	0.0 (-0.5, 0.6)	0.923
	0-6	18,842	0.93	-1.7 (-0.6, 4.0)	0.141	22,029	0.15	-0.4 (-1.2, 0.4)	0.295
Congestive heart failure	0	59,507	1.54	0.8 (-0.2, 1.9)	0.120	76,926	0.09	-0.1 (-0.2, 0.0)	0.104
	0-3	41,892	0.96	0.6 (-0.5, 1.7)	0.290	58,762	0.14	0.0 (-0.3, 0.3)	0.995
	0-6	44,293	0.93	0.9 (-0.5, 2.3)	0.189	58,354	0.15	-0.1 (-0.5, 0.4)	0.691
Ischemic heart disease	0	77,670	1.54	-0.0 (-0.9, 0.9)	0.958	112,847	0.09	-0.0 (-0.1, 0.1)	0.776
	0-3	53,781	0.96	-0.5 (-1.4, 0.4)	0.309	84,473	0.14	0.2 (-0.1, 0.4)	0.169
	0-6	58,188	0.93	-1.0 (-2.1, 0.2)	0.105	85,812	0.15	0.4 (0.0, 0.8)	0.032
Myocardial infarction	0	30,249	1.54	0.1 (-1.4, 1.6)	0.866	38,112	0.09	0.0 (-0.2, 0.2)	0.963
	0-3	20,962	0.96	-0.4 (-1.9, 1.2)	0.632	28,936	0.14	-0.1 (-0.6, 0.4)	0.667
	0-6	22,427	0.93	-0.2 (-2.1, 1.8)	0.841	28,668	0.15	-0.2 (-0.8, 0.5)	0.602
Aged Sea Salt (AGS)					Residual Oil (RO)				
Outcome	Lag	N Cases	IQR (µg/m ³)	Excess Rate % (95% CI)	p-value	N Cases	IQR (µg/m ³)	Excess Rate % (95% CI)	p-value
Cardiac arrhythmia	0	53,931	0.69	0.8 (-0.3, 2.0)	0.167	53,931	0.71	-0.2 (-1.5, 1.2)	0.818
	0-3	40,634	0.63	0.0 (-1.6, 1.7)	0.992	40,634	0.63	0.1 (-1.9, 2.2)	0.891
	0-6	40,698	0.60	0.5 (-1.5, 2.6)	0.636	40,698	0.62	-0.9 (-3.3, 1.5)	0.450
Ischemic stroke	0	29,014	0.69	0.1 (-1.4, 1.7)	0.884	29,014	0.71	2.1 (0.2, 3.9)	0.027
	0-3	22,309	0.63	-0.5 (-2.6, 1.7)	0.675	22,309	0.63	0.6 (-2.1, 3.5)	0.659
	0-6	22,029	0.60	-1.3 (-4.1, 1.5)	0.360	22,029	0.62	1.3 (-2.0, 4.6)	0.453
Congestive heart failure	0	76,926	0.69	-0.5 (-1.4, 0.5)	0.342	76,926	0.71	-0.7 (-1.7, 0.4)	0.215
	0-3	58,762	0.63	0.1 (-1.3, 1.5)	0.889	58,762	0.63	0.6 (-1.0, 2.2)	0.455
	0-6	58,354	0.60	1.4 (-0.3, 3.2)	0.110	58,354	0.62	0.8 (-1.1, 2.7)	0.429
Ischemic heart disease	0	112,847	0.69	0.0 (-0.8, 0.8)	0.949	112,847	0.71	0.8 (-0.1, 1.6)	0.092
	0-3	84,473	0.63	0.4 (-0.8, 1.5)	0.537	84,473	0.63	1.8 (0.4, 3.1)	0.009
	0-6	85,812	0.60	0.4 (-1.0, 1.8)	0.593	85,812	0.62	1.3 (-0.3, 2.9)	0.116
Myocardial infarction	0	38,112	0.69	0.2 (-1.1, 1.6)	0.752	38,112	0.71	1.5 (-0.1, 3.0)	0.064
	0-3	28,936	0.63	1.3 (-0.6, 3.3)	0.177	28,936	0.63	2.5 (0.1, 4.9)	0.041
	0-6	28,668	0.60	-0.6 (-3.0, 1.8)	0.599	28,668	0.62	0.2 (-2.5, 3.0)	0.892
Road Salt (RS)					Industrial (IND) ^a				
Outcome	Lag	N Cases	IQR (µg/m ³)	Excess Rate % (95% CI)	p-value	N Cases	IQR (µg/m ³)	Excess Rate % (95% CI)	p-value
Cardiac arrhythmia	0	9,651	0.04	0.0 (-0.2, 0.2)	0.695	3,196	0.19	-2.4 (-7.2, 2.7)	0.359
	0-3	3,948	0.08	-0.7 (-2.1, 0.7)	0.335	---	---	---	---
	0-6	6,618	0.07	0.6 (-0.1, 1.3)	0.076	2,345	0.17	1.1 (-8.5, 11.8)	0.827
Ischemic stroke	0	5,949	0.04	0.1 (-0.2, 0.3)	0.498	2,085	0.19	10.8 (3.9, 18.1)	0.002
	0-3	2,373	0.08	2.5 (0.6, 4.4)	0.008	---	---	---	---
	0-6	4,145	0.07	0.5 (-0.4, 1.4)	0.256	1,572	0.17	-5.1 (-16.1, 7.3)	0.405
Congestive heart failure	0	13,620	0.04	-0.1 (-0.2, 0.1)	0.245	4,244	0.19	3.6 (-0.6, 8.0)	0.094
	0-3	5,836	0.08	0.1 (-0.9, 1.2)	0.808	---	---	---	---
	0-6	9,272	0.07	-0.4 (-0.9, 0.1)	0.108	3,138	0.17	5.7 (-2.4, 14.3)	0.172
Ischemic heart disease	0	15,110	0.04	-0.2 (-0.3, 0.0)	0.019	5,511	0.19	-1.6 (-4.9, 2.0)	0.381
	0-3	5,970	0.08	-0.6 (-1.7, 0.6)	0.319	---	---	---	---
	0-6	10,273	0.07	-0.3 (-0.8, 0.1)	0.145	4,015	0.17	-5.9 (-12.3, 0.8)	0.083
Myocardial infarction	0	7,682	0.04	-0.2 (-0.4, 0.0)	0.066	2,785	0.19	-0.3 (-5.3, 5.0)	0.914
	0-3	3,055	0.08	-0.8 (-2.2, 0.7)	0.285	---	---	---	---
	0-6	5,269	0.07	-0.5 (-1.1, 0.2)	0.167	2,043	0.17	-6.0 (-14.9, 3.8)	0.219

^a PM_{2.5} filters/measurements, on which PMF Sources were identified, were only available in Buffalo every 6 days.

of the other excess rates associated with IQR increases in RS contribution were < 0.0%. Similarly, although each IQR increase in IND contribution in the previous day was associated with a 10.8% increase in the excess rate of ischemic stroke hospitalization (95% CI = .9%, 18.1%), many of the other excess rates associated with IQR increases in IND contributions were < 0.0%. Although most excess rates of ischemic stroke, congestive heart failure, and myocardial infarction associated with IQR increases in BB contribution were > 0.0%, none were statistically significant. Similarly, although rates of ischemic stroke and congestive heart failure associated with IQR increases in OP contribution were generally positive, none were statistically significant. Last, when estimating the rate of each cause specific cardiovascular hospitalization associated with increased PM source contributions in the previous 1, 4, and 7 days, separately in the Before, During, and After periods, we found little difference in the period specific relative rates (See Supplemental Tables).

4. Discussion

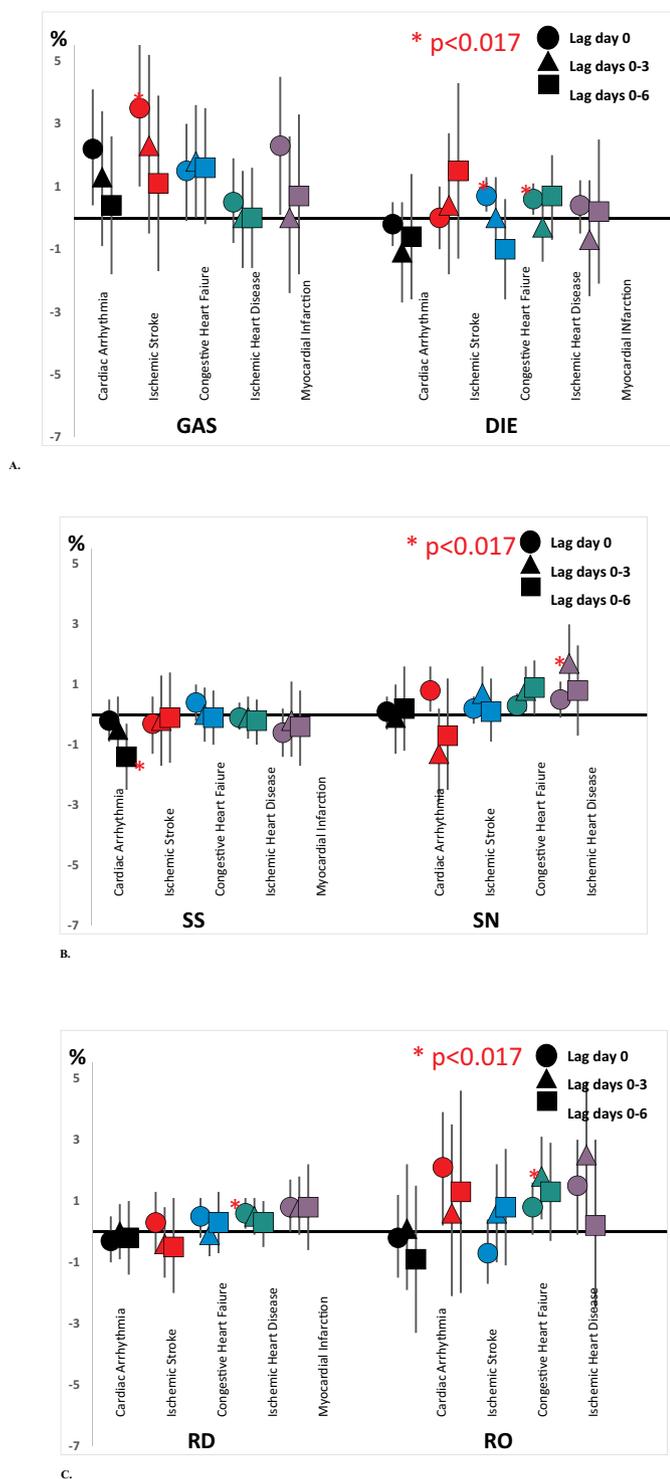


Fig. 1. Excess rate of acute cardiovascular event hospitalization by concentrations of A) spark ignition emissions (GAS) and diesel (DIE), B) secondary sulfate (SS) and secondary nitrate (SN), and C) road dust (RD) and residual oil (RO).

Previous studies have examined associations between acute health events (e.g. cardiorespiratory hospital admissions and emergency department visits) and short term increases in source apportioned PM concentrations (Andersen et al., 2007; Bell et al., 2014; Gass et al., 2015; Hopke et al., 2006; Ito et al., 2006; Krall et al., 2018; Laden et al., 2000; Mar et al., 2000; Ozkaynak and Thurston, 1987; Sarnat et al., 2008). Sarnat et al. found associations between increased respiratory and cardiovascular ED visits and gasoline vehicle, diesel vehicle, and biomass burning PM_{2.5} in Atlanta (Sarnat et al., 2008). Other studies

reported associations between PM₁₀ from biomass burning and increased respiratory hospital admissions in Copenhagen, Denmark (Andersen et al., 2007), gasoline and diesel PM_{2.5} and increased pediatric asthma ED visits in Atlanta (Gass et al., 2015), and respiratory hospital admissions and PM_{2.5} from road dust in Massachusetts and Connecticut (Bell et al., 2014). Krall et al. apportioned daily PM_{2.5} concentrations measured in Atlanta, Birmingham, St. Louis, and Dallas into PM_{2.5} from biomass burning, diesel vehicles, gasoline vehicles, dust, coal combustion, and metals, but only PM_{2.5} from biomass burning was acutely associated with respiratory ED visits (Excess risk = 0.6%–0.8%) over the next few days (Krall et al., 2018). Although these studies examined respiratory outcomes, our finding of cardiovascular hospitalization triggering by traffic related PM_{2.5} sources is consistent with these studies reporting greater risks/rates associated with traffic PM sources.

Zhang et al. suggested that because only secondary organic carbon concentrations were increasing in recent years when the increased toxicity of the PM_{2.5} was identified, additional exposure to oxidants and the related oxidative stress and inflammation would be potential drivers of the increased rates of hospitalizations (Zhang et al., 2018). All of these factors can be associated with either the likely presence of reactive oxidative species (ROS) or the ability to induce ROS in situ. The strongest site-by-site correlations between resolved source contributions and SOC were for the spark-ignition vehicle source. GAS was the only source whose contributions increased between the three periods (Masiol et al., 2019). There was an increase in the number of registered vehicles in the state. There were also important changes in the fuel formulation between 2010 and 2014 to reduce the concentration of benzene in the fuel (U.S. EPA 2019). The shift to increasing use of gasoline direct injection (GDI) in light-duty vehicles likely also contributed to the increased contribution of GAS to the ambient PM_{2.5} concentrations although newer GDI vehicles certified to stricter emissions standards do not produce more SOA than older port fuel injection engines (PFI) (Zhao et al., 2018). The r² values between SOC and GAS were 0.423, 0.548, 0.504, 0.303, 0.533, 0.533 for Albany, the Bronx, Buffalo, Manhattan, Queens, and Rochester, respectively. Thus, for all but Albany and Manhattan, > 50% of the SOC variance was related to the spark-ignition mass contributions. These results suggest that gasoline vehicles were an important source of precursor species and secondary organic aerosol (SOA) (Bahreini et al., 2012; Gordon et al., 2013; Gordon et al., 2014; Hayes et al., 2013). Fresh SOA would include peroxy radicals and peroxides and be strongly oxidizing (Chen et al., 2011; Docherty et al., 2005). Mills et al. found that even brief exposures to dilute diesel exhaust promoted myocardial ischemia and inhibited endogenous fibrinolytic capacity in men with stable coronary heart disease (Mills et al., 2007). Wang et al. showed that SOA, diesel and biodiesel exhaust particles generated significant amounts of H₂O₂ (Wang et al., 2012). Thus, GAS and DIE particles could contribute to both exogenous and endogenous ROS (Hopke, 2015).

Road dust (RD) represents non-exhaust traffic emissions containing a number of transition metals like copper, iron, and zinc. These primary emissions result from non-exhaust emissions including brake and tire wear (Padoan and Amato, 2019). Such metals can induce the formation of free radicals via Fenton-like reactions (Halliwell and Gutteridge, 1984; Strlic et al., 2003). RO would also represent a source of redox-active metals such as nickel and vanadium. Lippmann et al. reported that ambient nickel concentrations were associated with acute increases in heart rate and decreases in heart rate variability in mice and with increased mortality in people (Lippmann et al., 2006).

Both SN and OP represent secondary particles with SN primarily observed in the winter when the level of photochemical activity is low and ammonium nitrate becomes the dominant particle type with respect to particle surface area on which carbonaceous species can condense. Thus, SN could just represent a surrogate for the condensed ROS being advected by the locally formed nitrate particles. OP is primarily observed during the summer months when there is sufficient

photochemistry occurring to produce significant amounts of secondary sulfate and secondary organic aerosol (SOA). OP is thought to be an indicator of secondary organic aerosol (Squizzato et al., 2018b), and may represent more aged secondary organic aerosol that has been transported into the area with little associated reactive oxygen species (ROS). Chen et al. found that the lifetime of terpene producing reactive oxygen species was of the order of 6 to 7 h, so only recently formed secondary organic carbon (SOC) would likely have significant amounts of associated reactive oxygen species (Chen et al., 2011). Thus, the lack of association with OP may reflect its low reactive oxygen species concentration. Secondary sulfate may represent more aged aerosol in which much of the initially deposited reactive oxygen species have reacted away.

The other factors such as AGS, FSS, BB, and IND would not generally include strongly oxidizing constituents. There have been some suggestions of effects of wood smoke on cardiovascular outcomes (Croft et al., 2017; Rich et al., 2018). However, a recent review concluded that the evidence base for the cardiovascular effects of wood smoke is weak and that wood smoke exposures are highly variable due to the multifactorial nature of wood smoke creation (Adetona et al., 2016).

There were several strengths of our study including a large sample size resulting in increased statistical power, uniformly collected and coded hospitalization data in New York State from 2005 to 2016, and a concurrent multi-year source apportionment analysis across urban centers in New York state providing an assessment of acute health associations with individual PM sources. However, there were also several limitations to consider. First, cases within 15 miles of a PM_{2.5} monitoring site were assigned the same values of PM_{2.5} source contributions for a specific day, regardless of how close they lived to the site, which likely resulted in exposure misclassification. This misclassification error is likely a combination of Berkson and classical error, resulting in a bias toward the null and underestimates of effect (Bateson et al., 2007; Zeger et al., 2000). Second, there was a change in the hospital admission diagnosis codes used in SPARCS starting October 1, 2015 (shift from ICD-9 to ICD-10). Certain ICD-9 codes could be divided into multiple more specific ICD-10 codes, possibly resulting in an undercounting of cases in our study. However, this should result in only a loss of statistical power and not bias, as the case-crossover design contrasts pollutant concentrations between two time periods within the follow-up time of each case. Third, the PMF analyses of Squizzato et al. were conducted as a single source apportionment at each site across the entire 12 years of the study period (2005–2016), with individual sources identified and named based on common chemical compositions across these 12 years (Squizzato et al., 2018b). However, it is possible that if the source apportionment was done on individual time periods separately (e.g. 2005–2007, 2008–2013, and 2014–2016), daily concentrations of individual source specific mass concentrations (e.g. SS) would be different from those used in this analysis. If we assume that this exposure misclassification is non-differential with regard to time (i.e. not different for case and control periods), then it again is likely a combination of Berkson and classical error, resulting in a bias toward the null and underestimates of effect. Fourth, although we defined statistical significance as $p < 0.017$ based on three estimates/test per pollutant/outcome association (i.e. 3 lag days), we have 5 outcomes per PM_{2.5} source contribution. Thus if we made a Bonferroni correction for 15 or 5 tests per PM_{2.5} source contribution, we would have overestimated the p -value to define statistical significance, making far few results be statistically significant. Last, like all case-crossover designs analyzed with conditional logistic regression, adjusting for possible overdispersion is difficult if not impossible (Armstrong et al., 2014), which could result in confidence intervals that are larger than reported.

5. Conclusions

Using a large database of hospitalizations of adult New York State residents from 2005 to 2016 and concentrations of PM_{2.5} sources

identified previously (Squizzato et al., 2018b), we found, as hypothesized, increased rates of cardiac arrhythmias and ischemic stroke associated with increased GAS concentrations in the previous few days, and increased rates of congestive heart failure and ischemic heart disease hospitalizations associated with increased DIE concentrations. We did not find any such associations with SS as hypothesized. This null SS finding may just reflect the sharp decrease in sulfate concentrations in New York State (Squizzato et al., 2018a) and its reduced role as a transport vector for reactive species condensed onto its surface. Although RD, RO, and SN concentrations were also associated with increased rates of acute cardiovascular hospitalizations, there were no such associations with other sources. These findings suggest the role of spark ignition and diesel vehicle emissions, non-traffic emissions such as tire and brake wear, ROS residual oil combustion emissions for large building heating in New York City, and advected by nitrate particles in the triggering of acute cardiovascular events. These findings are consistent with the proposed hypothesis of Zhang et al. of the triggering of acute cardiovascular events by oxidants associated with secondary organic aerosols and oxidative potential associated with transition metals (Zhang et al., 2018). However, this will require confirmation of whether these sources in locations other than New York State produce similar rates of hospitalizations for these cardiovascular outcomes.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envint.2019.02.018>.

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