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Article

Associations Between Emergency Room Visits for Respiratory Diseases and Exposure to Zip Code Level Criteria Air Pollutants in New York State

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Highlights

Outdoor air pollution poses a significant risk for emergency room visits for respiratory diseases. We have assessed the frequency of ER visits for asthma and COPD among individuals living near to point source emissions of criteria air pollutants. Point source pollution is small relative to total air pollution but results in statistically significant elevation in ER visits for asthma and COPD among individuals living in a zip code containing a point source of criteria air pollutants.

Abstract

We assess associations between emergency room (ER) visits, scaled to per 10^5 population per year, for asthma and chronic obstructive pulmonary disease (COPD), two of the most common respiratory diseases, and zip-code level exposure to criteria air pollutants (CAPs) coming from point sources in New York State (NYS) from 2010 to 2018. Exposure data on point source CAPs was retrieved from the United States Environmental Protection Agency (USEPA) National Emission Inventory (NEI) database and ER visits for asthma and COPD were acquired from the New York State Department of Health (NYSDOH) Statewide Planning and Research Cooperative System (SPARCS). To account for within-county variability we used log-linear mixed effects models, adjusted for year, sex, age category, county level poverty, smoking, $PM_{2.5}$, volatile organic compounds (VOCs) and CAPs sources within the study period. Results show significant associations between ER visits for asthma and COPD and most of the pollutants in the study, even after adjusting for the effects of poverty and smoking. The findings suggest that zip-code level point source criteria air pollutants, while comprising a small portion of total air pollution, poses a modest but significant contribution to the risk of respiratory disease-related ER visits.

Keywords: point source emission; criteria air pollutants, asthma; COPD; national emission inventory; statewide planning and research cooperative system

Introduction

Air pollution is a well-established risk factor for respiratory morbidity and emergency room (ER) utilization. Yet, most research has emphasized particulate matter and broader ambient measures, with fewer studies isolating the contribution of local point-source emissions. In our prior New York State study, we evaluated zip code-level point source volatile organic compounds (VOCs) from the National Emissions Inventory (NEI). We found compound-specific patterns and interactions associated with ER visits for asthma, COPD, and respiratory infections [1]. The present study extends this line of work by focusing on a different pollutant class, criteria air pollutants (CAPs) from point

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sources, and by quantifying their associations with ER visits for asthma and COPD across New York State from 2010 to 2018.

Asthma and chronic obstructive pulmonary disease (COPD) are respiratory diseases known for affecting the quality of life of people of all ages [2,3]. They pose serious public health concerns and are estimated to have caused millions of deaths worldwide. Asthma is a chronic disease, but asthma attacks are a reversible respiratory event that is characterized by a response to hypersensitivity of airways, while COPD, for which asthma is one of the risk factors, is characterized by non-reversible airway obstruction [2,4]. Asthma attacks are manifested as intermittent and reversible airway obstruction, while COPD is progressive and irreversible [5]. Both diseases are disorders that are associated with increased inflammation [6]. Also, some patients with airway diseases have features of both asthma and COPD [7], indicating that both diseases can cause airway obstruction and are associated with chronic inflammation of the airways [8]. Both asthma and COPD exacerbations are responsible for approximately 1.5 million and 2 million yearly visits to the emergency room (ER) respectively in the United States (US) [2,9].

Ambient air pollution accounts for an estimated 8% of the portion of disease burden for respiratory infections [10]. Asthma development and exacerbation is linked to air pollution from fossil fuel combustion in traffic, power plants, and industrial facilities [11]. The relationship between air pollution and asthma attacks has been well-established particularly in countries with rapid urbanization and industrialization [12]. Our group has previously reported adverse respiratory effects of outdoor air pollution in Karachi, Pakistan [13], Jeddah, Saudi Arabia [14] and New York State [1].

When inhaled, ambient air pollutants induce airway inflammation and oxidative stress in bronchial epithelial cells, which often lead to the development of asthma or COPD [15]. This is supported by epidemiological and clinical investigations suggesting that exposure to outdoor air pollutants including criteria air pollutants (CAPs) induces airway inflammation, hyper-responsiveness and oxidative stress leading to the exacerbations of asthma and COPD [16–18]. Several studies conducted in different parts of the world have found that day-to-day increases in pollution levels are associated with the exacerbation of asthma.

Zheng et al.[19] undertook a meta-analysis to quantify associations between short-term exposures to ozone (O_3), carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and particulates (PM_{10} and $PM_{2.5}$) and asthma-related ER visits and hospital admissions (HAs). The study found associations between these pollutants and significant increased relative risks (RRs) in asthma ER visits and hospital admissions (HAs) with O_3: RR=1.009 (1.006, 1.011), CO: RR=1.045 (1.029, 1.061), NO_2: RR=1.018 (1.014, 1.022), SO_2: RR=1.011 (1.007, 1.015), PM_{10}: RR=1.010 (1.008, 1.013), and $PM_{2.5}$: RR=1.023 (1.015, 1.031). The study concluded that short-term exposures to the criteria pollutants account for increased risks of asthma-related ER visits and HAs that constitute considerable healthcare utilization and socioeconomic burden.

Additional studies of air pollution have documented relationships between ambient air pollution and respiratory disease related ER visits for children, the most susceptible group. Strickland et al., [20] conducted a study to investigate short-term associations between ambient air pollutant concentrations and ER visits for pediatric asthma. A total of 91,386 children aged 5 to 17 years that visited the ER were collected from 41 metropolitan Atlanta hospitals between 1993 and 2004. The study results showed association between the ambient pollutants and pediatric asthma ER visits even at relatively low ambient concentrations, O_3: RR=1.062 (1.031-1.093), NO_2: RR=1.036 (1.018-1.055), CO: RR=1.023 (1.006-1.041), $PM_{2.5}$: R=1.020 (1.002-1.039), and PM_{10} [RR=1.020 (1.003-1.038)]. The study concluded that ambient pollutants contribute to the burden of ER visits for pediatric asthma.

Byers et al. [21] also undertook a time-series study to estimate short-term associations between daily changes in SO_2, $PM_{2.5}$ and O_3 and daily asthma-related ER visits in Indianapolis, US. The study population comprised of 165, 056 asthma-related ER visits from 2007 to 2011. The study results show interquartile range increases in 3-day moving averages for SO_2 significantly associated with an increased risk of 3.3% (0.2%, 6.5%), especially during the warm season for age group 5-44.

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A multi-city assessment study by Alhanti et al. [22] investigated short-term relationships between ER visits for asthma and exposure to ambient O_3, CO, NO_2, SO_2, and fine particulate matter ($PM_{2.5}$) in Atlanta (1993-2009), Dallas (2006-2009), and St. Louis (2001-2007). The study was age stratified by using city-specific daily time-series analyses. The study results suggest that age and race are susceptibility factors for asthma exacerbations in response to air pollution. Effects were stronger for the 5-18-year-olds, and there were stronger associations with O_3 and NO_2 particularly among non-whites [RRs of 1.15 (1.11, 1.19)] per 28 ppb O_3 and RRs=1.09 (1.06, 1.11) per 12 ppb of NO_2 than among whites [RRs =1.01 (0.96, 1.06)] per 28 ppb of O_3 and RR=1.02 (1.00, 1.05) per 12 ppb of NO_2. The results also showed stronger association among males than females for CO and NO_2 with associations among males (RRs =1.05 (1.03, 1.06) per 0.5 ppm of CO and RRs=1.07 (1.05, 1.09) per 12 ppb of NO_2 than among females [RRs=1.01 (0.99, 1.03)] per 0.5 ppm of CO and RRs=1.03 (1.01, 1.06) per 12 ppb of NO_2.

Similarly, a time stratified case-crossover study investigating associations between short-term fluctuations in ambient air pollution concentrations and asthma ER visits in Windsor, Canada was conducted by Lavigne et al. [23]. The study observed significant associations between 1-day lagged exposure to SO_2, NO_2, CO, O_3 and ER visits for asthma. Additionally, significant association was also observed for 1-day lagged exposure to CO and asthma visits among children throughout the year with OR=1.15 (1.02-1.31). In conclusion, positive associations between ambient levels of SO_2, NO_2, CO, O_3 and ER visits for asthma were found, particularly among children.

Another common respiratory disease that is considered in this study is COPD which is characterized by progressive irreversible airflow limitation and chronic inflammation of the lungs. COPD costs the US around $29.5 billion in direct costs, and $20.4 billion indirect costs [24]. While outdoor air pollution is not the major cause of COPD, it can be an important trigger for exacerbations of symptoms resulting in the necessity of going to the ER.

Epidemiological studies have investigated the short-term effects of outdoor air pollution on COPD-related ER visits, HAs, and mortality, and most of these studies report significant positive associations for exposures to criteria pollutants. One such study [25] was a systematic review that includes 59 studies in which the authors evaluated associations between short-term exposure to CAPs and the risk of COPD exacerbations. The result showed an association between short-term exposure and increased risk for COPD exacerbations. SO_2 and NO_2 exposure showed more significance especially in low-/middle-income countries, SO_2 [RR=1.012 (1.001, 1.023)] and NO_2 [RR=1.019 (1.014, 1.024)].

DeVries et al. [26] also conducted a case crossover analysis to assess associations between short term exposures to SO_2, NO_2, and $PM_{2.5}$, and COPD exacerbations among 168 patients in central Massachusetts between 2012 and 2013. The study found significant associations between short-term SO_2 exposure and increased COPD exacerbation risk [OR = 2.45 (1.75-3.45)] per 1 ppb increase, and short-term exposure to NO_2 showed an association, but not as strong as the one for SO_2 [OR = 1.17 (1.05-1.30)] per 1 ppb increase. $PM_{2.5}$, however, did not show a positive association.

Faustini et al. [27] conducted a large 4-year study in Rome by following COPD patients (n=145,681) aged 35+, and a comparison group of people without COPD (n=1,710,557). COPD patients showed higher mortality rates due to $PM_{2.5}$, PM_{10}, and NO_2 exposures but the comparison group did not, and PM_{10} showed a five times larger effect estimate for total mortality. The observed effect of PM_{10} was 3-7 times higher in the COPD patients 3.5% (-0.1% to 7.2%) than in non-COPD patients 0.7% (-0.8% to 2.2%). Respiratory mortality among COPD subjects was $PM_{2.5}$ [interquartile range (IQR)=11 $\mu g/m^3$) 11.6% (2.0% to 22.2%) and NO_2 (IQR=24 $\mu g/m^3$) 19.6% (3.5% to 38.2%)]. The authors concluded that COPD patients are more susceptible to air pollutants such as PM_{10} and NO_2.

As documented above, there is strong evidence that air pollution increases risk of asthma and COPD. However, most of these studies consider total outdoor air pollution instead of point sources [1,28,29] and a few studies focused on individual point sources [30–32]. Point source pollution is just a minor part of the total air pollution exposures. However, this study was meant to determine

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whether emissions from the point source that are considered small can still contribute to respiratory disease exacerbation.

The goal of this study therefore was to assess the associations between rates of ER visits for asthma and COPD and CAPs exposure from all point sources in New York as reported in the EPA NEI dataset from 2010 to 2018 in relation to living in zip codes with point sources of CAPs. This is possible since the ER data is available at a zip code level and we know the zip code of each point source from the NEI data. This project will look at all point sources at zip code levels in New York and their associations with resident's ER visits for asthma and COPD from 2010 to 2018.

Criteria Air Pollutants and Respiratory Diseases

The United States Environmental Protection Agency (USEPA) listed the six common air pollutants as CAPs under the Clean Air Act in the 1970s. The primary CAPs include CO, SO_2, NO_2, O_3, PM and Pb. Short or long-term exposures to these pollutants are known to cause adverse health effects that often lead to hospitalizations or ER visits [33]. In some cases such exposure can lead to premature death [34,35].

Carbon Monoxide and Respiratory Diseases

CO is a colorless, odorless, and tasteless gaseous pollutant primarily from traffic or industry [36], produced by incomplete combustion of fossil fuels such as in motor vehicles [37] and cigarette smoke [38]. It is a ubiquitous air pollutant [39] and its toxicity is the most common type of fatal air poisoning in most countries including the US. CO is responsible for hundreds of deaths and thousands of ER visits every year [40]. The pathophysiological mechanism on the effect of CO is tissue hypoxia, due to its ability to bind with hemoglobin to form carboxyhemoglobin [41] and prevent the delivery of oxygen to tissues. Therefore, it is not surprising that exposure to an air pollutant that reduces delivery of oxygen would exacerbate diseases that already have reduced the delivery of oxygen to tissue.

In the US, exposure limit in the workplace has been set by the Occupational Safety and Health Administration (OSHA) at 50 ppm time-weighted-average (TWA) over 8 hours, 25 ppm short-term exposure limit, and 200 ppm ceiling, while the National Institute for Occupational Safety and Health (NIOSH) sets a recommended exposure limit of 35 ppm 8 h TWA [40].

Epidemiological studies have found that ambient CO has significant adverse effects on public health worldwide [36] and has been linked to increases in ER visits for asthma, COPD and other respiratory diseases [11]. It is also responsible for approximately 15,000 ER visits for respiratory diseases and 500 related deaths annually. To examine the effects of particulates and CO concentrations on asthma exacerbation among urban children, Evans et al. [42] conducted a pilot study to explore the relationship between asthma exacerbation and ambient concentrations of particles and CO. The results showed that ultrafine particles ($PM_{0.1}$) and CO increase exacerbation risk in urban children. IQR for $PM_{0.1}$ =2088 p/cm^3 [OR=1.27 (0.90-1.79)] and CO IQR= 0.17 ppm, [OR=1.63 (1.03-2.59)]. Their findings regarding CO and pediatric asthma events were consistent with previous studies showing increases in the risk of ER visits and hospitalizations for asthma in children.

Song et al. [43], with a total of 72,430 hospitalized cases in Ganzhou, Southeast China conducted a time series study to evaluate the association and the exposure-response relationship between ambient CO exposure and the risk of hospitalization for total and specific respiratory diseases including asthma, COPD, upper respiratory tract infection, lower respiratory tract infection, and influenza-pneumonia. Results showed CO exposure was significantly associated with hospitalization risk for all the respiratory diseases and further indicated that for each 1 mg/m^3 increased in CO at lag 0-2, hospitalizations for total respiratory diseases increases. Asthma increased by OR =17.74 (1.34%, 36.8%), COPD increased by OR =12.45 (2.91%, 22.87%). Women were more susceptible to ambient CO exposure-associated hospitalizations for asthma. The authors concluded that they found significant positive exposure-response relationships between ambient CO exposure and exposure-associated respiratory hospitalizations.

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Similarly, an ecological time series study, including 4,534 COPD hospitalizations in Ahvaz, Iran, carried out by Raji et al. [44] found a positive association between ambient CO exposure and COPD hospitalizations [RR=1.643 (1.233–2.191)].

Another time-series study conducted by Zhao et al. [45] examined short-term association between ambient CO and ER visits for respiratory diseases in Dongguan, China from 2013 to 2017 with a total of 89,484 outpatient visits for respiratory diseases including asthma, COPD, pneumonia and bronchiectasis cases. Results showed every IQR increase in CO at lag 0-3 corresponded to 5.62% (3.24%, 8.05%) for all respiratory diseases, 8.86% (4.89%, 12.98%) for asthma, 6.67% (0.87%, 12.81%) for bronchiectasis and 7.20% (2.35%, 12.29%) for pneumonia. The study concluded that short-term exposure to ambient CO was associated with increased risk of outpatient visits for respiratory diseases.

Lead Exposure and Respiratory Diseases

Lead (Pb) is an environmental toxin that is associated with numerous adverse health effects in children and adults [46]. It is a persistent metal in all parts of the environment, in air, water and soil, and is primarily derived from a variety of manufactured products like leaded gasoline, paints, ceramics, solders, water pipes, hair dye, cosmetics, airplanes, farm equipment, shielding for x-ray machines [47]. And it is very toxic to the nervous system [46].

Exposure occurs through ingestion of Pb-contaminated substances and inhalation of Pb particles that come from the burning of Pb-containing materials, such as leaded gasoline and residential paint are the primary routes of exposure to Pb [47,48]. And exposure to Pb plays a major role in exacerbating respiratory diseases [47], including COPD, pulmonary dysfunction, antioxidant activity [49], asthma [50], and neurodevelopmental impacts [48]. Correspondingly, soil and water Pb distribution have been shown to be associated with patterns of respiratory disease burden in Iran [51]. Pb-induced asthma includes effects on immune balance, oxidative stress, and inflammatory responses [50], resulting to seizures, headache, coma and even death [52]. While air levels of Pb have been dramatically reduced in the US, it is still a problem at some specific sites. However, there is little release of Pb from point sources in NYS. Since Pb exposure was very low and variable, we decided not to include it in the study analysis.

Particulate Matter and Respiratory Diseases

PM is of great public health concern because smaller particulates can penetrate deep into the lungs and reach the pulmonary alveolar region. This is particularly the case for $PM_{2.5}$ and ultrafine particulates ($PM_{0.1}$) [53,54].

Studies have shown correlations between $PM_{0.1}$ and different respiratory diseases in different parts of the world. For example, Bergmann et al. [54] examined associations between short-term exposure to $PM_{0.1}$ and mortality and hospitalizations in Copenhagen, Denmark. The results showed significant associations between exposure to $PM_{0.1}$ and hospitalizations for asthma and mortality for COPD. One IQR increase in $PM_{0.1}$ was associated with an OR=1.04 (.01, 1.07), lag 0-4, and 1.02 [1.00, 1.04], lag 0-1, was associated with COPD mortality [OR=1.13 (1.01, 1.26)] and asthma hospitalization [OR=1.08 (1.00, 1.16)] at lag 0-1. The study findings showed that short-term exposure to $PM_{0.1}$ can trigger respiratory disease mortality and morbidity.

$PM_{2.5}$ has also been associated in multiple epidemiological studies with ER visits for respiratory diseases [55,56] and has also been found to cause lung function reduction and airway inflammation [57], COPD, and asthma exacerbations [58–60]. A multicity time-series study involving 112 cities in the US conducted by Zanobetti & Schwartz [61] showed that a 10-$\mu g/m^3$ increase in 2-day averaged $PM_{2.5}$ resulted in a 1.68% increase (1.04-2.33) in respiratory deaths.

It has been suggested by multiple studies that PM may exacerbate asthma symptoms and increase incidence risks of asthma [62,63]. The global burden of outdoor air pollution on asthma ER visits in 2015 alone was estimated to be between 5 and 10 million globally. This was attributable to

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PM, where 12% of these estimates were observed in China [16]. Duan et al. [64] indicated for every 10μg/m^3 increase in $PM_{2.5}$ concentration, the risk of hospitalization increases by 1.61% in COPD patients in the US, and 0.82% in Beijing, China.

Although most studies focus on the smaller particulates, thinking the larger particles are usually removed from the respiratory tracts and do not enter the alveoli, some studies have found associations between larger particulates and respiratory diseases. Kang et al. [65] in their nationwide retrospective cohort study of 121,423 adults in South Korea found associations between PM_{10} exposure and mortality for severe exacerbation of respiratory diseases. But if one only measures PM_{10}, that measure will include smaller particulates that may in fact be the responsible factor.

Another study on PM_{10} was conducted in London, United Kingdom by Canova et al. [66]. This was a case-crossover study to investigate PM_{10} induced hospital admissions for asthma and COPD. The study found that every 10μg/m^3 increase in PM_{10} was related to an increase in asthma or COPD admission rate, especially in lag 0-3 days [OR=1.35 (1.04-1.76)].

Sulfur Dioxide and Respiratory Diseases

SO_2 is one of the six criteria pollutants in the air quality index that is emitted from natural and anthropogenic sources [67]. SO_2 is generated from the burning of sulfur-containing fuel like coal and is one of the prevalent air pollutants released from natural sources such as volcanoes or anthropogenically from burning of fossil fuel and biomass at large industrial plants such as oil refineries and power stations [68]. Recent studies have shown SO_2 is also a biological gas in various mammalian tissues [69], and people with asthma are especially susceptible to its effects [25]. Short term exposures of asthmatic individuals to elevated levels of SO_2 while exercising at a moderate level may result in breathing difficulties, wheezing, chest tightness, and shortness of breath [70]. Orellano et al. [71] conducted a systematic review and meta-analysis to evaluate the effect of short-term exposure to ambient SO_2 on all-cause and respiratory mortality. The study found that every 10μg/m^3 in acute SO_2 exposure was significantly associated with all-cause mortality [RR=1.0059 (1.0046-1.0071)], and respiratory mortality [RR=1.0067 (1.0025-1.0109)]. The authors concluded that there were positive associations between short-term exposure to ambient SO_2 and all-cause and respiratory mortality.

A cohort study comprised of 351 asthmatics and 327 non-asthmatic children in Puerto Rico from 2009 to 2010 was conducted by Rosser et al. [72]. The study evaluated the effects of annual average 1-hour daily maximum SO_2 on asthma, atopy, total IgE, and lung function. Results showed annual SO_2 exposure (per 1 ppb) was significantly associated with asthma [OR=1.42 (1.05-1.91)] and atopy [OR=1.35 (1.02-1.78)]. The conclusion was that SO_2 exposure is linked to asthma and atopy, and long-term SO_2 exposure also showed association with reduced FEV1/FVC, particularly in asthmatics.

SO_2 exposure has been correlated with increased overall ER visits for asthma, COPD, upper respiratory infection, pneumonia, dysrhythmia, hypertension, abdominal pain, depression, and headache [73]. Health effects and symptoms related to this pollutant include burning to the nose and throat, sore throat, difficulty inhaling deeply, altered sense of smell, and increased susceptibility to respiratory infections. SO_2 combines with water in the respiratory tract to form sulfuric acid [67] which is likely responsible for some of the symptoms. SO_2 has been linked to an accelerated decline in lung function, which is a special concern for developing children and people who have underlying COPD, asthma, or other chronic respiratory diseases [73].

Madaniyazi & Xerxes [16] indicated that the association between SO_2 exposure and exacerbation of asthma has been investigated extensively, and it has been confirmed to be a key risk factor for asthma even at low levels. They performed a meta-analysis on the short-term exposure to SO_2 and the mortality of asthma in East Asian countries reported that hospital utilization for asthma among children increased by 5.7% for every 10μg/m^3 increase in the daily mean concentration of SO_2. Like NO_2 and O_3, SO_2 has also been strongly associated with asthma and exacerbations. Elevated SO_2 levels can cause coughing, mucus secretion, and aggravation of asthma [21,32,74].

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Nitrogen Oxides and Respiratory Diseases

NO_x are produced from natural sources such as volcanic activity, biomass burning and bacterial activity [75] or from anthropogenic sources such as burning fossil fuels in stationary sources like industrial plants, or in motor vehicles [76]. NOx causes respiratory irritation and can trigger cell damage and inflammatory processes throughout the respiratory system, from the nose to the pulmonary alveoli [77]. Nitric oxide (NO), nitrous oxide (N_2O) and nitrogen dioxide (NO_2) generate nitrogen oxides (NOx), which are considered primary air pollutants [78]. NO is a free radical that produces oxidants with low water solubility and can trigger cell damage and inflammatory processes throughout the respiratory system, from the nose to the pulmonary alveoli [79,80]. NO_x causes respiratory problems such as coughing, dyspnea, wheezing, bronchospasm, and pulmonary edema at high concentrations [81]. NO_x is a free radical-producing oxidant with low water solubility, and a deep lung irritant [68]. It is a precursor to ground level ozone and can participate in the secondary formation of $PM_{2.5}$. Nitric oxide has diverse roles on the immune system from innate resistance to suppression of Th1 functions to induction of oxidative injury [82]. A longitudinal study was conducted by Ghosh et al. [77] in the Czech Republic to assess ambient NO_x exposure and early childhood respiratory illnesses. Children were followed from birth to 4.5 years of age. For the first 2 years of life, an IQR increase in the 30-day average of NO_x resulted in an OR=1.31(1.07, 1.61) for bronchitis and OR = 1.23 (1.01-1.49) for two- to 4.5-year-olds. Results from this longitudinal study demonstrate associations between NOx and respiratory illnesses, especially for bronchitis.

Many studies have reported the effects of short-term exposure to NO_x on human morbidity and mortality [83]. Meng et al. [84] in their multilocation analysis in 398 cities found that a 10 $\mu g/m^3$ increase in NO_2 concentration on lag 1 day was associated with 0.47% (0.21% to 0.72%) increases in respiratory mortality. The authors therefore concluded that NO_2 is associated with considerable health risks even at levels below health-based standards and guidelines, including the current WHO air quality guidelines.

NO_x exposures can exacerbate existing respiratory disease by impairing the functions of epithelial cells and alveolar macrophages, contributing to airway inflammation]24]. Increased levels of NO_x have been correlated with increased use of ER visits, specifically for asthma, COPD, respiratory infections, otitis media, cardiovascular diseases, hypertension, dysrhythmia, abdominal pain, depression, and headache [73]. A recent study was conducted by Kowalska et al. [85] to assess the risk related to NO_x and NO_2 concentration increase, and daily hospital visit due to bronchitis and asthma exacerbation in Poland. Results showed a significant association between outpatient visits and hospitalizations for bronchitis and asthma exacerbation and daily NOx concentrations. The strongest relationship was observed in the case of NO_2, and outpatient visits due to bronchitis, RR = 1.434 (1.308-1.571). In addition to traffic related air pollution, evidence from previous studies has shown that people who live near contaminated sites known as point sources showed abnormalities of serum immunoglobulins and suffer from more frequent hospitalization for respiratory infections, chronic bronchitis, and COPD [86]. Power plants account for approximately 16% of NO_x emissions in the US [70].

We aim to assess associations between zip code level point source CAPs emissions in NYS and ER visits for asthma and COPD over the period 2010-2018, and to assess relative strengths of associations between each pollutant and the outcomes.

Materials and Methods

The health data used is information on ER visits due to asthma and/or COPD in all New York State regulated hospitals and other health facilities with emergency rooms in all NYS counties except New York City from 2010 to 2018. Information on asthma and COPD ER visits was retrieved from the NYSDOH SPARCS system database. This data is legislatively mandated to be reported to the NYSDOH upon patient discharge from inpatient and ER facilities. The SPARCS data does not include federal institutions such as the veterans' affairs hospitals, Indian health services or psychiatric

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facilities. SPARCS data used in this study includes date of birth, sex, race/ethnicity, zip code of residence and the International Classification of Diseases (ICD) code for the specific disease requiring ER admission.

Asthma and COPD cases include hospital ER visits from 2010 through 2018 where asthma and/or COPD was the primary reason for visit. There were 643,066 ER visits for asthma and 254,549 for COPD, with primary diagnosis using the ICD, 9th and 10th revisions, Clinical Modification (CM). The study looked at asthma (ICD-9-CM code 493 and ICD-10-CM code J45) and COPD (ICD-9-CM codes 490-496 and ICD-10-CM codes J40-J47). The outcome was defined as the number of cases during the period from 2010 to 2018, aggregated by gender, race, and age groups. Age data for asthma patients was categorized into six levels (0-5, 6-19, 20-44, 45-64, 65-74, 75+ years), and for COPD, four age levels (35-44, 45-59, 60-74, and 75+). Ages 35-44 years have been used as the median age range at which COPD is usually diagnosed [87](DeMeo et al., 2022). This age group was therefore used as reference age for COPD in this study. Patients younger than 35 with COPD diagnoses were dropped. The age reference used for asthma in this study was 45-64.

Data on Pollutant Exposure

Air pollution sources are categorized as point, non-point, on-road, non-road, and event, according to EPA NEI. This study was limited to the point source emissions of the criteria pollutants because NEI provides point source exposure data at the zip code level, but not the other emission sources listed above. However, data for the other sources such as on-road, non-road and non-point data are provided at the county level. Since the ER data is at the zip code level, this study is limited to exposure to point source pollution. To account for within-county variability, county level total VOCs and CAPs were used as adjusting variables since the CAPs are present with VOC pollution at county level and the point-source pollution is superimposed on that coming from on-road, non-road, and non-point sources.

A point source emission is one produced by large and stationary sources like power plants, industries, airports, or smaller non-industrial sources. Point source pollution information for $PM_{2.5}$, CO, Pb, NOx, and SO_2 for the years 2011, 2014, and 2017 was retrieved at the USEPA NEI website. However, data for O_3, which is also a CAP, is not available in the NEI dataset, and there was so little release of Pb that it was not considered. Pollutant site latitude and longitude locations were then associated with the zip code in which the facility was located using a scheme that minimized the absolute great circle distance between the zip code centroid and the site location. Data from the USCB was used to determine the land area in square miles in each zip code. For each pollutant, zip code, and year, the pollution per square mile was calculated by summing all point source contributions of the pollutant and dividing by the land area size of the zip code region. The workable data was in pollution per square mile.

Table 1. Total emissions (counts) for each criteria pollutant at point source zip code level in NYS for the study period, based on NEI exposure data for 2011, 2014, 2017 given in tons.

Pollutants	Exposure in tons
Carbon monoxide (CO)	186,081
Nitrogen oxides (NOx)	145,773
Lead (Pb)	5,067
Fine particulate matter ($PM_{2.5}$)	13,074
Coarse particulate matter (PM_{10})	18,868
Sulfur dioxide (SO_2)	126,752

Data on Poverty

Poverty rates by zip code were downloaded from the United States Census Bureau (USCB) website for the study period. The official poverty measure defines poverty by comparing pretax

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money income to a poverty threshold that is adjusted by family composition. Since poverty information was not available 2010 to 2011, data for the year 2012 were used for years 2010-2012. Families are considered poor if their total income falls below a certain threshold. All families that fell below the threshold were categorized as below mean, and those above the threshold were categorized as above the mean in this study.

Smoking Data

To adjust our associations for smoking (a risk factor for both asthma and COPD), we used county level prevalences calculated by the Behavioral Risk Factor Surveillance System (BRFSS). The BRFSS is a continuous, state-based surveillance system that collects information about modifiable risk factors for chronic diseases and other leading causes of death, and it is the nation's premier system of health-related telephone surveys that collect state data. The county level data was used to cover a wider range and scope. Data by year was averaged over the study period and matched with zip codes which evenly covered the geographical research area. Smoking data were obtained at the county level since the zip code level data were not available.

Statistical Analysis

Missing Exposure Data. The years for which the NEI reports data were 2011, 2014, and 2017. Reporting for these years had inconsistencies across zip codes. For instance, in some zip codes emitting units did not report in all given years. This can be attributed to the fact that although reporting is mandatory both at site and unit levels, in the state of NY this is often not enforced. Since point sources do not move, it is reasonable to assume that units still produced emissions even though emissions were not reported. Therefore, missing data for those years were inputted using emitting sites and unit IDs per zip code. For each zip code and site ID, missing unit IDs were inserted, and their emissions were replaced by the mean value of emissions reported assuming emissions were the same and for the samples provided by that unit when it did report. If the unit did not report at any time during the period sampled (2011 to 2017), it will not appear in zip code level emission totals. The largest source of missing data is cryptic and is not reflected in this study data because it consists of emitting units within a site and a zip code that failed to report in any of these years. This is a limitation of this dataset.

The total number of zip codes reporting may not change much after imputation, but the pollutant totals do. Changes in zip codes during the study period were resolved by using a reference set of codes from 2011. The total number of zip codes in the state of NY is estimated at 1792, and a little less than that reported some point source pollution for at least one of the target pollutants in 2011, 2014, and 2017, which also had cases of diseases in this study. Those zip codes with disease cases but without point source data over the study period were given a point source emission rate of zero. Zip codes with zero population were assumed to be post office boxes and were not considered in the analysis. A study by Madani and others (2023) did similar analysis on different air pollutants.

Single Pollutant Models. Datasets were created by merging data across years for each pollutant (available for years 2011, 2014, and 2017). All years were analyzed together. Pollutant data from 2011 was associated with zip code disease rates for 2010, 2011, and 2012. Pollutant data from 2014 was joined to disease data from 2013, 2014, and 2015, and pollutant data from 2017 were used with disease data from 2016, 2017, and 2018. Data from all years were then stacked to complete the file.

Log-linear mixed effects regression models with random intercepts at the county level were used in this study to analyze ER visit rates for asthma and COPD and their associations with CAPs exposure. This model was chosen because it allows for both fixed and random effects, and the data in the study has hierarchical structures that include both zip code and county level data. A p-value of <0.05 was considered statistically significant, and the R-squared likelihood ratio test was used as a measure of goodness of fit.

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Adjusted associations between the rates of ER visits, scaled to per 10^5 population, and pollutants at zip code level were estimated using log-linear mixed effects models with a random effect to account for within-county variability. Models were adjusted for sex (reference level female), age category (reference level at 45-64 for asthma, 35-44 for COPD), a poverty category variable (reference below median poverty), average county level smoking, study year (reference level 2010), and county level VOCs and CAPs from all sources. All numeric covariates are standardized and the outcome case rate by zip code was log-transformed to achieve normality. All data preparation and analysis were performed with the R programming language and R studio software version 2022.07.1.

Results

Association Between Asthma and the Criteria Air Pollutants in the Study

Estimates, 95% CIs and the corresponding *p*-values for associations between asthma ER and CAPs exposures are shown in Table 1. All pollutants are positive and significantly associated with asthma except for $PM_{2.5}$. SO_2 showed the most effect closely followed by NOx and then CO. PM_{10} showed significance, but the effect size is not as strong as the gaseous pollutants. This is clearly shown in Figure 1.

Table 1. β Estimate, lower and upper CIs, and *p*-values for the CAPs and asthma ER visits.

Outcome	Pollutant	Estimate	95% CI	*P*-value*
Asthma	CO	0.024	0.017, 0.031	<0.0001
	NOx	0.032	0.017, 0.047	<0.0001
	$PM_{2.5}$	0.001	-0.012, 0.014	0.898
	PM_{10}	0.0167	0.0, 0.034	0.057
	SO_2	0.1169	0.096, 0.138	<0.0001

**p*-values give significance of adjusted associations between outcome and zip code level pollutant exposure.

Figure 1. shows the exposure-response relationship between CAPs and asthma ER visits from 2010 to 2018 by zip code given every 0.05 standard deviation increase in exposure. SO_2 showed the largest association with asthma ER visit, followed by NOx and CO. The effect size form PM_{10} is greater than that of $PM_{2.5}$. The figure again indicates the gaseous pollutants showed the largest magnitude effect sizes in association with asthma.

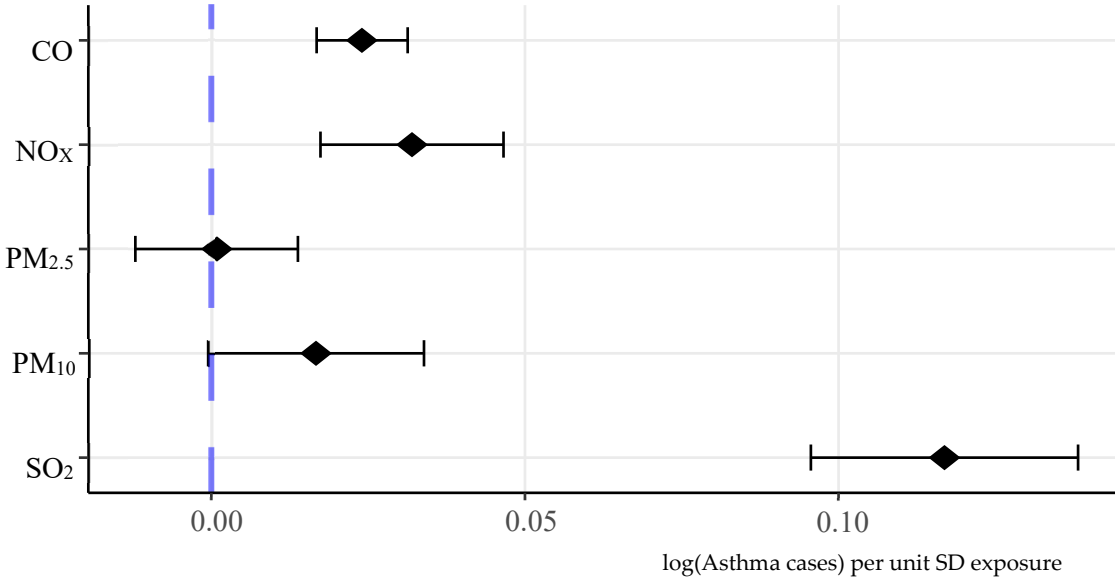

Figure 1. Effect sizes for estimated associations for criteria pollutants and asthma.

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Association Between COPD and Criteria Air Pollutants

Table 2. displays the β estimates, 95% confidence intervals, and p-values for the CAPs in the study, and their associations with ER visits for COPD. All the pollutants showed positive and statistically significant associations with COPD. Again, the gaseous pollutants showed the most effect, with NOx leading followed by SO_2 and CO.

Table 2. Estimates, CIs and *P*-values for CAPs and ER visits for COPD.

Outcome	Pollutant	β Estimate	95% CI	*p*-value*
COPD	CO	0.029	0.022, 0.037	<0.0001
	NOx	0.041	0.029, 0.053	<0.0001
	$PM_{2.5}$	0.009	0.002, 0.018	0.0145
	PM_{10}	0.012	0.004, 0.021	0.0024
	SO_2	0.029	0.021, 0.037	<0.0001

**P*-values give the significance of adjusted associations between outcome and zip code level pollutant exposure.

Figure 2 shows the effect sizes of the pollutants in the study by zip code over the study period, given every 0.02 standard deviation increase in exposure. NOx showed the most effect followed by CO and SO_2. The particulates' sizes are smaller than the gaseous pollutants. And this is consistent for the other diseases in the study.

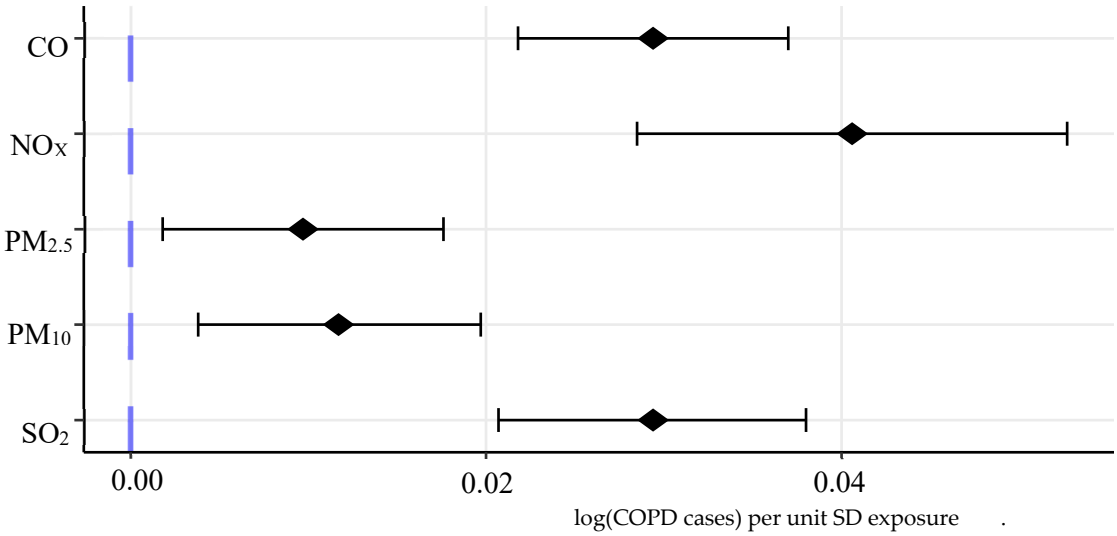

Figure 2. Effect sizes for estimated associations of criteria pollutants and COPD.

Discussion

Air pollution is a major environmental issue affecting respiratory health globally. This study complements, rather than duplicates, our earlier VOC-focused analysis [88] by examining point source criteria air pollutants, which differ in sources, atmospheric behavior, exposure profiles, and regulatory relevance. Although both studies use NEI point source data and similar zip code level modeling frameworks, the scientific question here is distinct, namely whether CAP emissions from local point sources, even as a small fraction of overall air pollution, are associated with elevated asthma and COPD ER visits after accounting for key confounders and co pollutants (including PM2.5 and VOCs). The observed pollutant specific associations support the interpretation that local CAP point sources contribute modestly but significantly to respiratory morbidity, underscoring the importance of evaluating multiple pollutant classes when assessing community level health impacts and informing targeted mitigation near emitting facilities.

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Criteria Air Pollutants and Respiratory Diseases

The goal of this study was to assess associations between point source CAPs and ER visits for asthma and COPD at zip code levels in NYS from 2010 to 2018, and to identify which of these pollutants increases the risk of an ER visit for both diseases. The respiratory system is very vulnerable to the hazardous effects of air pollution, and respiratory diseases are significant causes of ER visits. Air pollution, including CAPs, has been extensively studied and proven to be a major risk factor that leads to significant adverse health outcomes. Both short- and long-term exposures to air pollutants can adversely affect respiratory health leading to ER visits, hospitalization, and in some cases even death by inducing airway inflammation, even at very low concentrations [89,90]. ER visits for asthma and COPD in this study showed significant adjusted associations with CAPs exposure when considering CAPs exposure was just point sources. This association was observed for all years even after adjusting for poverty and smoking in mixed effects regression models that allow for county level variation. Single pollutant adjusted regressions showed that CO, NOx, and SO_2 contributed the largest to both disease outcomes. These are also the pollutants that contribute the largest amount of pollution from point sources. The results of this study are consistent with findings in the literature cited, suggesting that exposure to CAPs is a risk factor associated with an increase in the number of ER visits for both asthma and COPD.

CAPs and Asthma

Studies have indicated that air pollution contributes to increased asthma prevalence and symptom onset [28,91,92] and asthma exacerbations [71]. This study adds to the many research studies that report that exposure to the CAPs increases the risk of ER visits for asthma, and that among the pollutants in this study, NOx and CO have the largest effects followed by SO_2. $PM_{2.5}$, however, did not show any significant association with asthma. This may be because the amount of $PM_{2.5}$ coming from point sources is very small relative to the amount coming from other sources, because there is other evidence showing clearly that $PM_{2.5}$ does contribute to asthma attacks. It was a surprise to find a significant association with PM_{10} but not $PM_{2.5}$. However, similar results have been previously reported, as mentioned above. Even though most larger particulates are trapped and removed by ciliary action and mucosa, they still may trigger irritation and inflammation. The effects of all of these pollutants on the onset and or exacerbation of asthma were confirmed in previous epidemiologic studies. For instance, Gorai et al. [49] in their GIS based approach for assessing the association between air pollution and asthma in NYS, found significant associations between exposure to CAPs with asthma prevalence rate in NYS, US.

CAPs and COPD

COPD is a common respiratory disease, affecting 5-10% of the US population. Smoking is known to be a major cause of development of COPD, and when an individual already has impaired respiratory function, it is not surprising that superimposed exposure to CAPs increases the need for treatment in the ER. COPD related death has continued to increase, and it is one of the leading health burdens worldwide that accounts for almost 3 million deaths annually. Outdoor air pollution has contributed to its increased incidence and prevalence [93,94]. From the results in Table 2 of this study, there is strong positive and statistically significant association between the pollutants and ER visits. As was the case with asthma, the associations were strongest with the gaseous pollutants, which also were the largest component of pollutants coming from point sources. For COPD both PM_{10} and $PM_{2.5}$ showed significant associations. These associations are confirmed by published associations between exposure to these air pollutants and ER visits for COPD ([25,95]. For example, Cirera et al. [96] reported that ambient air levels of SO_2 and NO_2 relate positively and significantly with a substantial increase in asthma and COPD ER visits.

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Strengths and Limitations

Strengths of this study include its temporal length (2010-2018), and use of NEI data to provide source and magnitude information for spatially distributed Criteria Air Pollutants.

However, our study has several limitations. First, ecologic design does not permit assessment of causal relationships between point source exposures and emergency room visits, so we report adjusted single pollutant associations. Second, reporting air pollution is mandatory but patchy, so the NEI data may represent only a fraction of actual emissions. Finally, criteria air pollutants were sampled on just three time points during our 9-year study period (years 2011, 2014, 2017) and include just known point source outdoor pollution emission sources. To address this limitation, we adjusted our models at county level for pollution from all sources.

Conclusions

Most pollutants in the study were positive and statistically significant with asthma, indicating a detrimental effect for relatively local point sources of pollution. All pollutants showed associations with asthma ER visits except $PM_{2.5}$. For COPD, all the pollutants showed significant positive associations with the outcome. The gaseous pollutants (CO, NOx, and SO_2) showed consistent positive associations and showed the most effects. For the particulates, PM_{10} showed positive associations with asthma and COPD but with smaller effect size, while $PM_{2.5}$ also showed positive association with COPD but not asthma. Cirera et al. [96] confirmed in their study that ambient air levels of SO_2 and NOx related positively and significantly with a substantial increase in asthma and COPD ER visits.

While point source emissions of CAPs is small relative to total emissions coming from traffic, building heating and other sources of fossil fuel combustion, our study shows that these point source emissions are associated with more frequent ER visits among those living in the same zip code that contains the point source. Furthermore, we find that the gaseous pollutants, SO2, NO_X and CO, have a stronger impact on morbidity than particulates. Whether this is due to the relative amount of emissions from the different point sources or to the relative respiratory toxicity remains to be determined.

Author Contributions: Conceptualization: TL and DOC; investigation: TL; data curation: LEJ, TL and NAM; methodology: LEJ; software: LEJ, TL, and NAM; validation: LEJ; formal analysis: LEJ; resources: DOC; writing, original draft: TL, LEJ, NAM, and DOC; writing—review and editing: TL, LEJ, NAM, and DOC; supervision: DOC, LEJ. All authors contributed significantly to editing the manuscript and have approved the final version. This work was a part of the PhD dissertation of TL.

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Institutional Review Board Statement: The use of SPARCS data without individual identifier has been reviewed and declared to be "exempt" by the Institutional Review Board of the University at Albany.

Conflicts of Interest: All authors declare that they do not have conflicts of interest related to this manuscript. DOC has served as an expert witness in cases regarding health effects of air pollution but does see any conflict regarding this study.

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