Point source emissions of EPA-monitored criteria pollutants and the rates of ED visits and hospitalizations for asthma in Connecticut, 1996-2002

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POINT SOURCE EMISSIONS OF EPA-MONITORED CRITERIA POLLUTANTS AND THE RATES OF ED VISITS AND HOSPITALIZATIONS FOR ASTHMA IN CONNECTICUT, 1996-2002

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POINT SOURCE EMISSIONS OF EPA-MONITORED CRITERIA POLLUTANTS
AND THE RATES OF ED VISITS AND HOSPITALIZATIONS FOR ASTHMA IN

By

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ABSTRACT

**Background** Four criteria air pollutants are highlighted in the clinical and epidemiological literature as major asthma irritants; coarse particulate matter (PM$_{10}$), sulfur oxides (SO$_{2}$ and SO$_{3}$), nitrogen oxides (NO and NO$_{2}$) and volatile organic compounds (VOCs). **Methods** Poisson regression coefficients were calculated for asthma ED visits and hospitalizations in Connecticut in relation to PM$_{10}$, SO$_{X}$, NO$_{X}$ and VOC pollutant emissions and PM$_{10}$SO$_{X}$ or NO$_{X}$VOC interactions. **Results** In the unadjusted Poisson regression models, a one standard deviation increase in PM$_{10}$ was associated with an increase of about 37 ED visits per 10,000 population (P<.0001) and that a one standard deviation increase in VOCs was associated with an increase of about 32 ED visits per 10,000 population (P<.0001). After controlling for sociodemographic factors (race, age, gender, socioeconomic status), the results of the Poisson regression indicated that a one standard deviation increase in VOCs was associated with an increase of about 7 ED visits per 10,000 population (P<.0001) and that a one standard deviation increase in SO$_{X}$ was associated with an increase of about 1 ED visits per 10,000 population (P<.0001) in Connecticut. **Conclusions** The results of the Poisson regressions suggest a role for PM$_{10}$, VOCs and SO$_{X}$ in relation to asthma hospital admissions in Connecticut. But, temporal factors and geographical modeling are needed in future studies to better assess pollutant concentrations in relation to annual and seasonal fluctuations in emissions and the geographic clustering of asthma episodes near major point sources.
ACKNOWLEDGMENTS

Several people have been instrumental in allowing for the completion of this project. I would like to thank especially Dr. Mark Mitchell, President and Founder of the Connecticut Coalition for Environmental Justice, for suggesting that I look at environmental exposures in relation to potential health effects such as asthma and pointing me in the right direction for gathering data from the Department of Environmental Protection and the Department of Public Health. I would also like to thank my thesis advisors Drs. Arthur Dubois and Mark Cullen from the John B. Pierce Laboratory and the Yale Occupational and Environmental Medicine Program, respectively, for their kind encouragement and patience throughout the duration of this thesis. Finally, I would like to thank my academic advisor Dr. Stanislav Kasl who provided advice about approaching my thesis topic and the EPH professors and other MPH students that generously shared their time and expertise in the areas of data management and statistical analysis.
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INTRODUCTION

The development and severity of asthma, a chronic inflammatory condition of the airways, is influenced by a multifactorial etiology that includes genetic, immunologic and environmental factors (Busse, 2001; Bracken, 2000). Episodic symptoms of reversible airway obstruction and airway hyper-responsiveness occur with this disorder as a response to a variety of nonspecific and specific airway stimuli (Plopper, 2000; Moorman, 2007). Both nonspecific irritants and allergens, the latter being host-specific antigens that cause specific immune reactions, stimulate asthma pathophysiology though chemical and neural mechanisms of bronchoconstriction or mediator-induced airway inflammation from prostaglandins, histamine and leukotrienes which are released from the airway mast cells (Boushey, 1994). The primary features of asthma include airway inflammation in addition to tissue injury and subsequent structural changes that are collectively referred to as airway remodeling (Homer, 2005). Risk factors for childhood asthma include male sex, history of allergic disease, parental history of asthma, early-life stressors and infections, obesity, and exposure to indoor allergens, tobacco smoke and outdoor pollutants (King, 2004; Cullinan, 2003). The risk factors for the onset of adult asthma include female sex, airway hyperresponsiveness, modifiable lifestyle factors such as smoking, diet or the use of oral contraceptives or postmenopausal hormones, and sensitization from occupational exposures to dust, fumes or smoke (King, 2004; Chan-Yeung, 1995; Cullinan, 2003).

The prevalence of asthma has increased in industrialized countries over the past 20 years and over 20 million currently have asthma in the United States (Mannino, 1998). Based on data from the Behavioral Risk Factor Surveillance System (BRFSS), which is coordinated by the Centers for Disease Control and Prevention (CDC), asthma is one of the most common chronic conditions in children and the leading cause of disability in children (Miskell, 2005). For the
period 2001-2003, an average annual 6.2 million children (aged <18) and 13.8 million adult persons had asthma in the United States. The at-risk-based rate of emergency department visits for those with current asthma was 11.2 per 100 for children compared to 7.8 per 100 for adults, and 21.0 per 100 for blacks compared to 7.0 per 100 for whites. The at-risk-based rate of outpatient department visits for those with current asthma was 10.5 per 100 for children compared to 5.0 per 100 for adults, and 19.9 per 100 for black children compared to 8.7 per 100 for white children, and 10 per 100 for black adults and 4.3 per 100 for white adults (Moorman, 2004). But, the BRFSS data and other nationally representative surveys indicate that residents of urban settings, regardless of race or household income, are at increased risk of asthma after controlling for a large number of associated demographic variables (Aligne, 2000; Grant 1999). These findings suggest that asthma in population subgroups may be a combination of individual genetic susceptibility and long-term exposure to environmental risks in the modern urban environment (Weiss, 1999).

Multidisciplinary public health researchers are beginning to consider disparate exposures to environmental pollution as a contributor to health inequities for respiratory illness. The ununiform increase in asthma prevalence and morbidity among subgroups in the United States suggests that there are geographic and sociodemographic variations in environmental exposures (Wright, 2007). For instance, several environmental health studies reveal that low-income and minority communities tend to reside near environmentally hazardous facilities and bear a larger share of the health burden from exposures to toxins (Brulle, 2006). Systematic meta-analyses of studies regarding environmental inequalities confirm that race and class are predictive of differential proximity to environmental risks and the timing and extent of remediation actions (Brown, 1995; Szasz, 1997; IOM 1999). Other studies have suggested that exposure to high
levels of ozone or particulate matter in vulnerable populations such as children significantly enhances the risk of respiratory symptoms, asthma medication use, and reduced lung function (Gent, 2003). But the translation of environmental inequalities into health disparities through possible synergistic or cumulative effects of risk factors in the urban environment remains under study. The field of environmental epidemiology requires improved methods for conducting aggregate data (ecologic) studies on the environmental determinants of health effects (Prentice, 1993).

The four “criteria”¹ air pollutants PM₁₀, SOₓ, NOₓ and O₃ that are thought to trigger asthma primarily arise from anthropogenic combustion sources such as the burning of fuels by internal combustion engines in stationary or mobile sources.² Coarse particulate matter (PM₁₀), which consists of solid and liquid aerosol particles that are less than 10 microns in diameter, can become lodged in the respiratory tract and aggravate existing cardiopulmonary disease (Pope, 2002). The sources of PM₁₀ include crushing or grinding operations that create dust, e.g. construction sites. Sulfur oxides (SOₓ), which are colorless gases that are odorless at low concentrations, constrict breathing passages and cause wheezing, shortness of breath, and coughing especially in people with asthma. SOₓ arises from the burning of fuels that contain sulfur such as oil and coal fired power plants, industrial boilers, residential heating and motor vehicles. Nitrogen oxides (NOₓ), which are yellowish-brown and highly reactive gases that react with other chemicals in the air to form acid rain, may act as respiratory and pulmonary irritants (Samet, 1999). NOₓ sources include motor vehicle exhaust and high temperature fuel combustion in electric power generating facilities. Lastly, ground level ozone (O₃), which is a

¹ As required by the Clean Air Act, the Environmental Protection Agency (EPA) has set National Ambient Air Quality Standards (NAAQS) for six principal pollutants considered harmful to the environment and public health. These six “criteria pollutants” are particulate matter (PM), sulfur dioxide (SO₂), nitrogen dioxide (NO₂), ozone (O₃), lead (Pb) and carbon monoxide (CO) (US EPA website).
² “Stationary” refers to point source and area sources of emissions and “mobile” refers to both on-road and off-road mobile sources of pollutant emissions (US EPA website, 2008).
key contributor to smog and respiratory damage, is formed through a set of photochemical reactions between atmospheric NO\textsubscript{X} and organic hydrocarbons called volatile organic compounds (VOCs) that can be generally described by the following equation:

\[ \text{VOC} + \text{NO}_\text{X} + \text{heat} + \text{UV rays (sunlight)} = \text{ground level ozone (O}_3) \]

Unlike the other compounds, human activities do not emit much ozone directly and, therefore, the control of ozone has been primarily focused on its precursor pollutants NO\textsubscript{X} and VOCs, the latter a product of major painting and coating operations. In clinical and epidemiological studies, PM\textsubscript{10}, SO\textsubscript{X}, NO\textsubscript{X} and O\textsubscript{3} have been shown to exacerbate asthma, primarily by augmenting airway inflammation (Peden, 1999).

Based on data from the EPA Toxics Release Inventory (TRI), Connecticut has had greater reductions in reportable stack and fugitive emissions of hazardous air pollutants (HAPS) than the nation as a whole. (Stack emissions are emissions that have gone through the air pollution control device (APCD) and are released from the stack while fugitive emissions are emissions that escape capture by the APCD through leaks in equipment, pipe lines, seals, or valves.) The EPA Toxics Release Inventory (TRI) of the top ten chemicals released in 2003 for all states combined reveals that the 2003 stack emissions of HAPS were 0.30 of the original 1998 value, while fugitive emissions were 0.22 of the original 1998 value. The TRI for the state of Connecticut in 2003 reveals that over the reporting period of 1988 to 2003, stack and fugitive emissions of HAPS dropped from 14 million pounds per year to closer to 0.7 million pounds per year, a striking 0.05 of the original 1998 value. Since there was a possibility of early over-reporting of stack and fugitive emissions in Connecticut, a comparison of 1990 to 2003 emissions was also made and showed that in Connecticut the 2003 emissions were 0.10 of the 1990 value, which was close to the 0.05 from the initial TRI reporting. But, the health benefits
attributed to HAPs control strategies are uncertain due to TRI reliance on chemical weight reductions of emissions, rather than differences in potency and risk of each pollutant. (CT DEP, 2008)

The *Asthma in Connecticut Update* reports that in 2003 Connecticut had a lifetime asthma prevalence of 12.1% (313,000) and a current asthma prevalence of 7.7% (199,181) for Connecticut adults, rates that have been relatively steady since 1998 (Galvin, 2003). ED rates were generally higher among the younger age groups each year from 1995-2000 with an average annual 6,000 ED visits for asthma among children ages 0-14 years. The asthma hospitalization rate for children in Connecticut was lower than that for children in the United States, while the asthma hospitalization rate for children in Connecticut’s largest cities (Bridgeport, Hartford, New Haven, Stamford and Waterbury) was higher than the rate for the entire state and the US. Black children in Connecticut had an asthma hospitalization rate of 54.7 per 10,000, nearly five-times higher than the average annual rate for white children in Connecticut. Children in the state’s largest cities accounted for nearly 45% of all ED visits and hospitalizations although only 20% of Connecticut’s children live in these cities. Both ED visits and hospitalizations with a primary diagnosis of asthma showed seasonal pattern, with more hospital admissions occurring in the fall and the fewest occurring during the summer months.

Connecticut emissions of the top ten chemicals that contribute to criteria air pollutants are within EPA compliance,\(^3\) but recent findings indicate that respiratory effects from air pollutants can be seen at ever lower concentrations (Brunekreef, 2002). But much of the evidence for a relation between criteria pollutants and asthma aggravation has arisen from studies carried out in

\(^3\) Review of the Toxics Release Inventory (TRI) of the top ten chemicals released in Connecticut in 2003 showed that Connecticut’s stack and fugitive emissions are within EPA compliance (CT DEP website, 2008).
a single geographic region and over a short time frame (Schildrout, 2006). For the purposes of understanding asthma hospital admissions in relation to the release of air pollutants from point sources in Connecticut, I assessed four criteria air pollutants PM$_{10}$, SO$_X$, NO$_X$ and VOCs that are highlighted in the clinical and epidemiological literature as major asthma irritants. I hypothesized that the point source emissions of these pollutants, particularly PM$_{10}$ and the O$_3$ precursors referred to as VOCs, would be significantly associated with the rate of asthma ED visits and asthma hospitalizations between 1996 and 2002 in Connecticut.

**METHODS**

**Source of Data**

*Health data*

CHIME, Inc., a data collection and analysis service provider for the Connecticut Hospital Association (CHA), collects data on inpatient admissions, hospital-based ambulatory service and emergency department visits in the state. We utilized the CHIME data that had been extracted by the Connecticut Department of Public Health (DPH) Asthma Program on all hospital admissions for residents of the state who were admitted to a hospital (in Connecticut) with a primary diagnosis of asthma (ICD-9: 493), from hospital records for the years 1999–2001 (Miskell, 2005). Both the number of admissions through the emergency department and hospitalizations were considered in order to assess possible differences in elective admissions into the emergency department and acute events of asthma requiring hospitalization.\(^4\) According to CHIMES, the accuracy of the CHIMES reported diagnosis of asthma is validated by extensive error identification systems, using custom software with 160 edits to screen data for accuracy.

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\(^4\) Only the number of hospital admissions was used as a source of data, and not the rate per 10,000 hospitalizations, as I wanted to look at the hospital admissions rate per 10,000 population for the patient town of residence.
completeness, and consistency. CHIMES sends data error reports to each hospital for review and the corrected data is then returned to CHIMES for inclusion in the comprehensive hospital database (CHIMES, 2008).

*Environmental data*

Using a FOIA (Freedom of Information Act) request, point source emissions data for PM\textsubscript{10}, SO\textsubscript{X}, NO\textsubscript{X}, VOCs, Pb and CO was obtained from the Connecticut Department of Environmental Protection (DEP) Compliance Analysis and Coordination Unit in the Bureau of Air Management. Point source emissions refers to the estimated amount of pollutants generated from power plants, industrial boilers, petroleum refineries, industrial surface coatings and chemical manufacturing industries. Under the Title V program,\textsuperscript{5} DEP monitors point source emissions from stationary sources through the engineering calculations of the quantity of yearly or seasonal pollutants emitted from a specific source. DEP monitoring includes, but is not limited to, instrumental or non-instrumental methods, including periodic inspections, visual observations, work practice checks, and record keeping to document that an action has been taken or that a permit requirement has been met. Some examples of instrumental methods of monitoring include continuous emissions monitoring, periodic readings of parameters related to operating conditions, stack tests using EPA reference test methods, vendor or laboratory analytical testing, and manual inspections that include making records of process conditions or work practices. (CTDEP, 2008)

*Sociodemographic data*

\textsuperscript{5} The EPA Title V Operating Permits Program was created under the Clean Air Act to monitor the pollution control of large point sources (power plants, industrial boilers, petroleum refineries, industrial surface coatings and chemical manufacturing industries) and a limited number of small sources (dry cleaners, fast food restaurants and beauty salons).
For the purposes of data analysis, relevant demographics data for each town was collected from the US Census Bureau (Census, 2000). Data on race/ethnicity, gender, age distribution, poverty, and income per capita were identified for the analysis since these factors are correlated with both asthma hospital admissions and the concentration of the criteria air pollutants in the human health and environmental health literature. Towns were classified as urban or nonurban based on the US Census reported population density which is the population size divided by the total land area. The Census Bureau classifies as "urban" both urban areas that are made up of core census block groups or blocks that have a population density of at least 1,000 people per square mile and, an urban cluster that consists of surrounding census blocks that have an overall density of at least 500 people per square mile.

Data Analysis

Data Preparation

New town variables were created based on the reporting format of our data sources so as to facilitate the analysis; the statistical relationship between the independent variables PM$_{10}$, SO$_X$, NO$_X$ and VOCs and the dependent variables, ED visits for asthma and asthma hospitalizations. The DEP emissions data, which was initially reported by site address and a “principal communities” town in Connecticut, was subsequently grouped according to the 169 town variables listed in the US Census. (The Directory for the Local Directors of Health in Connecticut, which is printed by the CT DPH for the Local Health Administration Program, was referred to in order to change the ‘principal communities’ variables from the DEP data source into town variables that fit the format of the US Census data.) DPH, our source for health data, had grouped the asthma data for 20 adjacent towns into 10 sets of 2 neighboring towns. These
formatting adjustments for the data from the DEP and DPH sources left a total of 159 town variables to analyze the relationship between point source emissions and ED visits for asthma and asthma hospitalizations.⁶

Statistical Analysis

The SAS analysis included both parametric and nonparametric methods.⁷ In order to assess pollutant collinearity, the Pearson and Spearman correlations calculated pollutant-pollutant correlations. The independent group t-test was used to compare nonurban and urban settings using either the Satterthwaite t-test values or the pooled t-test depending on the unequal or equal variance of the specified variable. The Poisson regression calculated the coefficients for hospital admissions in relation to each pollutant emissions and pollutant interactions (PM₁₀SOₓ and NOₓVOC). Log-linear regressions calculated the potential percentage reduction in pollutant-attributable hospital admissions.

RESULTS

Correlation Analysis

There was a significant Pearson correlation between PM₁₀ and VOCs (r=0.97, p<.0001). For the Spearman correlation, there was a higher correlation between some pollutants after excluding influential (outliers and leverage) towns that had extremely high pollutants emissions. For

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⁶ The following towns were grouped: Colchester and Salem; Cornwall and Warren; Deep River and Killingworth; Griswold and Lisbon; Old Lyme and Lyme; Manchester and Bolton; Norwich and Preston; Seymour and Oxford; Stafford and Union; Woodbridge and Bethany.

⁷ Both tests were performed since large populations with a non-Gaussian distribution present few problems for parametric and nonparametric tests; parametric tests are robust and nonparametric tests are powerful. The central limit theorem ensures that parametric tests are robust for large samples even if the population deviates from a Gaussian distribution, and nonparametric methods are slightly more powerful than parametric tests.
example, after excluding the emission levels of pollutants for Middletown, Bridgeport, New Haven, Norwalk, and Milford, there was a significant Spearman correlation between each of the four pollutants.

Urban and Non-Urban Comparisons

Description of the Dependent and Independent Variables

The use of health care services for asthma by nonurban towns and urban towns was compared with independent group t-tests. Urban towns had a significantly higher mean number of visits to their emergency department for asthma ($P = .0069$) and a significantly higher mean number of hospitalizations for asthma ($P < .0001$). All of the towns with the highest emergency department visits and hospitalizations were urban towns, with the exception of Groton which is a nonurban town located in the southeast region of Connecticut. The independent group t-test was also used to compare the mean pollutant emissions between the group of urban towns and the group of nonurban towns. There were statistically significant urban-related differences in the mean pollutant levels for $\text{PM}_{10}$, $\text{NO}_X$ and VOCs at the 0.01 significance level, with the urban towns having a higher emissions level for each of these pollutants. There was not a significant difference between urban towns and nonurban towns for $\text{SO}_X$ emissions ($P=0.0754$). The urban towns included all of the top emissions towns with the exception of Montville, which is a small nonurban town located in the southeast region of Connecticut.

Sociodemographic Characteristics

As shown in Table 1, the 159 towns included 76 urban towns (47.8), defined as having a population density equal to or greater than 500 per square mile, and a total of 83 nonurban towns
(52.2%) with a population density below 500 per square mile. The age and sex distribution for
the age groups 0-17, 18-24, and 25-44 was not significantly different for nonurban and urban
towns. Nonurban towns, however, had a significantly lower percentage of individuals in poverty,
children (age 18 and below) in poverty, and elderly (65 and above) in poverty. Compared to
urban towns, nonurban towns also had a smaller percentage of nonwhite populations and a
higher percentage of non-elderly older adults and a higher percentage of adult females compared
to adult males.

**TABLE 1 Sociodemographic Characteristics by Urbanicity**

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>All Towns N = 159</th>
<th>Non Urban N=83</th>
<th>Urban N=76</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Population:</td>
<td>3,405,565</td>
<td>668,308</td>
<td>2,737,257</td>
<td></td>
</tr>
<tr>
<td>Age Distribution:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% 0-17</td>
<td>24.9 (2.81)</td>
<td>25.1 (2.57)</td>
<td>24.6 (3.04)</td>
<td>0.1123</td>
</tr>
<tr>
<td>% 18-24</td>
<td>6.5 (4.27)</td>
<td>6.3 (5.11)</td>
<td>6.8 (3.13)</td>
<td>0.2480</td>
</tr>
<tr>
<td>% 25-44</td>
<td>29.8 (3.14)</td>
<td>29.7 (3.42)</td>
<td>29.8 (2.82)</td>
<td>0.4127</td>
</tr>
<tr>
<td>% 45-64</td>
<td>25.3 (3.34)</td>
<td>26.5 (3.35)</td>
<td>24.1 (2.84)</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>% 65+</td>
<td>13.4 (3.53)</td>
<td>12.3 (3.30)</td>
<td>14.7 (3.36)</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Combined Sex and Age Groups:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Males &lt; 18</td>
<td>51.2 (1.27)</td>
<td>51.3 (1.59)</td>
<td>51.2 (0.78)</td>
<td>0.5761</td>
</tr>
<tr>
<td>% Females ≥ 18</td>
<td>48.8 (2.08)</td>
<td>48.7 (2.11)</td>
<td>48.8 (2.13)</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Poverty:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Individuals in Poverty</td>
<td>4.9 (4.08)</td>
<td>4.1 (2.31)</td>
<td>5.8 (5.26)</td>
<td>0.0049</td>
</tr>
<tr>
<td>% Children in Poverty</td>
<td>5.3 (5.97)</td>
<td>3.9 (2.95)</td>
<td>6.8 (7.80)</td>
<td>0.0013</td>
</tr>
<tr>
<td>% Elderly in Poverty</td>
<td>5.5 (3.31)</td>
<td>5.0 (3.13)</td>
<td>6.1 (9.83)</td>
<td>0.0076</td>
</tr>
<tr>
<td>Race/ Ethnicity:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% White</td>
<td>91.4 (11.18)</td>
<td>95.6 (3.76)</td>
<td>86.9 (14.44)</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>% Black</td>
<td>3.6 (7.37)</td>
<td>1.3 (2.24)</td>
<td>6.1 (9.84)</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>% Other</td>
<td>4.9 (4.70)</td>
<td>3.1 (1.85)</td>
<td>6.9 (5.91)</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>% Hispanic</td>
<td>4.0 (5.95)</td>
<td>1.8 (1.34)</td>
<td>6.3 (7.88)</td>
<td>&lt;.0001</td>
</tr>
</tbody>
</table>

Income per capita (in dollars):
- Q1 (25th percentile): 23952, 24899, 23310
- Median: 28229, 28961, 27689
- Q3 (75th percentile): 33925, 33925, 34032

*The Satterthwaite t-test values were used for the variables that had unequal variance between the urban and nonurban groups; all variables except for %0-17, %25-44, %45-64, %65+ and %elderly in poverty. For these variables, the pooled t-test values were used. Nevertheless, there was little difference between either p-value.‡ P-value reflects the halved value of the p-value from the two tailed t-test.
Log-Linear Regressions

Unadjusted linear regression equations were estimated to relate the natural logarithms of ED visits and hospitalizations for asthma to the natural logarithm of each the pollutant categories. Adjusted linear regression equations were then estimated to assess these associations after controlling for the covariates age, sex, poverty and income.

In the unadjusted models, a moderate amount of the variation in the log-transformed ED visits and hospitalizations was explained by the log-transformed pollutant emissions (See Table 2). ED visits and hospitalizations for asthma were significantly associated with each of the pollutant emissions in the unadjusted models (P<.0001). For the unadjusted PM$_{10}$ models, a one percent increase in average PM$_{10}$ emissions was associated with a 22.4% in the average ED visit rates and a 25.6% increase in hospitalization rates. For the VOC models, a one percent increase in average VOC emissions was associated with a 13.0% in the average ED visit rates and a 14.4% increase in hospitalization rates. For the NO$_X$ models, a one percent increase in average NO$_X$ emissions was associated with a 14.1% in the average ED visit rates and a 2.0% increase in hospitalization rates. For the SO$_X$ models, a one percent increase in average SO$_X$ emissions was associated with a 13.3% in the average ED visit rates and a 16.9% increase in hospitalization rates.

In the adjusted models, approximately 50% of the variation was explained by the overall model, which included each pollutant and the covariates. In the adjusted PM$_{10}$ models, a one percent increase in PM$_{10}$ was associated with a small and statistically insignificant increase in the average ED visit rates and a 6.6% increase in hospitalization rates (P=0.0750). The adjusted

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8 (In both the unadjusted and adjusted regression models the natural logarithm of the pollutant plus 1, or ln (pollutant +1), was used in order to account for towns with a value of "0" for the total point source emissions of a pollutant).
The x-axis for each graph represents the logarithm to the base 10 of the total pollutant emissions (recorded in tons) plus the number one, or log10 (total pollutant emissions + 1). The y-axis for each graph represents the logarithm to the base 10 of the rate of hospital admissions (recorded per 10,000 population), or log10 (rate of hospital admissions). The additional adjustment of the pollutant values was made in order to eliminate missing and negative data plots for the pollutants.
VOC models were associated with a small and statistically insignificant decrease in the average ED visit rates and a small and statistically insignificant increase in hospitalization rates. The adjusted NO\textsubscript{X} models were associated with a small and statistically insignificant decrease in the average ED visit rates and a 5.0% increase in hospitalization rates (P=0.0455). The adjusted SO\textsubscript{X} models were associated with a small and statistically insignificant decrease in the average ED visit rates and a 5.5% increase in hospitalization rates (P=0.0260).

Compared to the pollutants, sociodemographic characteristics significantly added to the overall goodness of fit for the adjusted models. Using the standardized estimates of the pollutant in each model as the reference, the non-pollutant independent variables had relatively more strength than the pollutant variables in the adjusted models. In only the SO\textsubscript{X} model for hospitalizations was the pollutant statistically significant and comparable to the strength of the other covariates in the adjusted model. In the adjusted SO\textsubscript{X} model for hospitalizations, only the parameter estimates for SO\textsubscript{X} (P=0.0260), the age group 45-64 (P= 0.0323) and poverty (P=0.0391) were statistically significant at the 0.05 level. Based on the standardized estimates, the 45-64 age group, poverty and SO\textsubscript{X} had a relative strength of 1:1:1, respectively, in explaining the rate of hospitalizations in this model. Similarly, in the adjusted NO\textsubscript{X} model for hospitalizations NO\textsubscript{X} was statistically significant and comparable to the strength of the covariates in the model. In the adjusted model for NO\textsubscript{X} and hospitalizations, only the parameter estimates for 45-64 age group (P=0.0237), poverty (P= 0.0312) and NO\textsubscript{X} (P=0.0455) were statistically significant at the 0.05 level. Based on the ratios of the standardized estimates, the 45-64 age group, poverty and NO\textsubscript{X} had a relative strength of 2:2:1, respectively, in explaining the rate of hospitalizations in this model.
The other adjusted models included covariates with significant beta estimates at the 0.05 level and statistically insignificant pollutant associations. For the adjusted PM$_{10}$ model for ED visits, income per capita (P=0.0005), poverty (P=0.0181) and the 18-24 age group (P=0.0367) were statistically significant at the 0.05 level. For the adjusted PM$_{10}$ model for hospitalizations, the 45-64 age group (P=0.0081) and poverty (P=0.0481) were statistically significant at the 0.05 level. For the VOC model for ED visits, income per capita (P=0.0005) and the 18-24 age group (P=0.0313) were statistically significant at the 0.05 level. For the VOC model for hospitalizations, the 45-64 age group (P=0.0027) and poverty (P=0.0485) were statistically significant at the 0.05 level. For the adjusted NO$_X$ model for ED visits, income per capita (P=0.0006), 18-24 age group (P=0.0207), poverty (P=0.0233) and “other” race (P=0.0263) were statistically significant at the 0.05 level with “other” race referring to the race-ethnicity groups not classified as white, black or Hispanic. Finally, for the adjusted SO$_X$ model for ED visits, income per capita (P=0.0004), poverty (P=0.0176) and the 18-24 age group (P=0.0398) were statistically significant at the 0.05 level.

Poisson Regression Analysis

In the unadjusted models for ED visits and hospitalizations, the predictors PM$_{10}$ and VOCs were statistically significant at the .0001 level. For ED visits and PM$_{10}$, the unadjusted Poisson regression model predicting ED visits from PM$_{10}$ was statistically significant with a p-value of <0.0001. For these data, the expected log count for a one-unit increase in PM$_{10}$ was 0.0037. This translated into an increase of about 37 ED visits per 10,000 for a one standard deviation increase in PM$_{10}$. For ED visits and VOCs, the unadjusted Poisson regression model predicting ED visits
from VOCs also yielded a p-value of <.0001. For these data, the expected log count for a one-unit increase in VOCs was 0.0032. This translated into an increase of about 32 ED visits per 10,000 for a one standard deviation increase in VOCs. The effect of SOX was also significant in the unadjusted model at the .0001 level but translated into an increase of only about 1 ED visit per 10,000. Similarly, for hospitalizations, a one standard deviation increase in PM10 or VOCs translated into an increase of about 37 hospitalizations per 10,000 and NOX translated into 1 hospitalization per 10,000.

The Poisson regression models were adjusted for the covariates (age, sex, poverty and income) in which these variables were held constant in the models. For the dependent variable asthma ED visits for, only the pollutants VOCs and SOX had statistically significant explanatory value. The expected log count for a one-unit increase in VOCs was 0.0007 (P<.0001). This translated into an increase of about 7 ED visits per 10,000 for a one standard deviation increase in VOCs while holding the other variables constant in the model. The adjusted ED visits and SOX model yielded a p-value <.0047 but this translated into an increase of less than 1 ED visits per 10,000 for a one standard deviation increase in SOX while holding the other variables constant in the model. For hospitalizations, PM10, SOX and NOX were significant in the model but a one standard deviation increase in these pollutants did not translate into measurable increases in hospitalizations per 10,000.

In the adjusted models, however, the covariates were more significantly associated with increases or decreases in the utilization of hospital services for asthma compared to the pollutants. For the towns, a higher proportion of people in the 45-64 age range (β= -.1054, p <.0001) and a higher proportion of males less than age 18 (β= -.1115, p<.0001) were associated with a significantly decreased risk of asthma ED visits. Similarly, a higher proportion of people
in the 45-64 age range (β = -.0952, p < .0001) and a higher proportion of males less than age 18 (β = -.0401, p < .0001) was associated with a significantly decreased risk of asthma hospitalizations for asthma. Urban residence (β = .1486, p < .0001), poverty (β = .0321, p < .0001), and the presence of a higher proportion of women over the age of 18 (β = .0468, p < .0001) were all strong predictors of asthma hospitalizations. However, urban residence, poverty and the presence of a higher proportion of women over the age of 18 did not provide much explanatory value for asthma ED visits.

DISCUSSION

Several epidemiologic studies have found associations between ambient air pollutants, particularly coarse particulate matter (PM$_{10}$), volatile organic compounds (VOCs), nitrogen dioxide (NO$_2$) and sulfur dioxide (SO$_2$), and increases in emergency department visits or hospital admissions for the respiratory symptoms characteristic of asthma (Leikauf, 2004). The biological plausibility of pollutant contribution as a contribution to asthma exacerbation, and thus asthma hospital admissions, has been confirmed by chamber studies and clinical studies (Leikauf, 2002). Ozone, nitrogen oxides, and suspended particulates all share a common property of being potent oxidants, either through direct effects on lipids and proteins or indirectly through the activation of intracellular oxidant pathways. Other pollutants such as sulfur oxides have been shown to increase the synthesis of the allergic antibody IgE in animals and human beings, which may increase sensitization to common allergens. By interacting together and with other environmental factors, pollutants can exert potential long-term effects such as irreversible tissue damage in allergic individuals (Brunekeefe, 2002).

The goal of this ecological analysis was to describe the cross-sectional relationship between the point source emissions of four of the EPA criteria pollutants, PM$_{10}$, VOCs, SO$_X$ and
NOX, and asthma ED visits and hospitalizations by town in Connecticut. The total annual pollutant emissions of PM10, VOCs, SOX and NOX from the point sources acted as a surrogate measure of population exposure to these pollutants in each town of Connecticut. Two important features of this study are that all of the towns were comprehensively assessed for total point source emissions and the entire observation period covered approximately 48 months of ED visits and hospitalizations. Although some of the associations reported in previous research were significant in the unadjusted linear regression and Poisson regression models, the effect sizes of exposure differences were generally smaller compared to the covariates in the adjusted models.

The results of the Poisson regressions highlighted the importance of the unadjusted Poisson regression models for PM10 and VOC point source emissions in the prediction of hospital admissions for asthma. Higher PM10 and VOC point source emissions in combination with various sociodemographic variables predicted higher ED visits for asthma. Even after controlling for age, sex, income, and poverty, PM10 and VOC continued to be associated with small increase in ED visits but not hospitalizations. After controlling for sociodemographic factors (race, age, gender, socioeconomic status), the results of the Poisson regression indicated that a one standard deviation increase in PM10 was associated with an increase of about 7 ED visits per 10,000 population (P<.0001) in Connecticut and that a one standard deviation increase in VOCs was associated with an increase of about 1 ED visits per 10,000 population (P<.0001) in Connecticut. In the adjusted models, SOX was associated with an increase of about 1 ED visit per 10,000 population (P<.0001). No conclusions could be made for the independent effects of nitrogen oxides or pollutant interactions that are mentioned in recent studies.

Previous findings from environmental health studies suggest that the increased asthma episodes in urban areas compared to nonurban areas are due to a combination of differences in
environmental exposures to respiratory irritants and the presence of susceptible populations (Seaton, 1994). The results of this population-level, cross-sectional study suggest that particulate matter (PM$_{10}$) and organic hydrocarbons (or VOCs) that are emitted from point sources may have a significant and independent association with asthma hospital admissions in Connecticut. Indeed, the urban towns in this study had significantly higher reported point source emissions of PM$_{10}$ (P<.0001), VOCs (P<.0001) and NOX (P<.0001) than in nonurban towns and a higher mean rate of asthma ED visits (P=.0069) and hospitalizations (P<.0001). Urban towns were also more likely to have a higher percentage of non-white populations (P<.0001), individuals in poverty (P=.0049), children in poverty (P=.0013), and elderly in poverty (P=.0269), all identified as susceptible populations in the asthma literature (Morman, 2004).

Furthermore, the analysis of the sociodemographic characteristics in relation to asthma ED visits and hospitalizations yielded some interesting findings, but these findings should be interpreted with caution based on the ecological nature of the study. Urban residence was a significant predictor of increased asthma hospitalizations (β=.1486, ρ < .0001) and a slightly decreased risk of ED visits (β= -0.0664, ρ < .0001). In fact, epidemiologic studies have documented that the relationship between air pollution and hospital admissions for respiratory illnesses may be the largest among urban areas and inner cities (Etzel, 2008). The differences in the risks for asthma hospitalizations and ED visits in this study may be reflective of urban-related differences in asthma severity. Nonurban residence was associated with an increased risk of ED visits but a decreased risk of hospitalizations while urban residence was associated with a decreased risk of ED visits but an increased risk of hospitalizations. These results indicate that although nonurban towns had more frequent ED visits they had a decreased risk of severe asthma cases that required hospitalization.
Both sex and age were associated with asthma ED visits and hospitalizations. In fact, epidemiologic studies consistently document a higher rate of hospitalizations for acute asthma among male children compared to female children and a higher incidence of asthma hospitalizations for adult females compared to adult male asthmatic patients (Skobeloff, 1992; Schatz, 2006). In this study, towns having a higher proportion of women over the age of 18 compared to men over the age of 18 were associated with a significantly increased rate of hospitalizations. Similar to documented studies on these groups, which do not show a significant difference in the number of ED rates for non-acute asthma in female and male adults, there were no large differences in ED visits for towns with a higher adult female-male ratio (Singh, 1999). Towns having a higher proportion of males less than age 18 were associated with a significantly decreased risk of asthma ED visits and hospitalizations. These findings may be in direct contrast with the literature that indicates that male children are at a higher risk of ED visits and hospitalizations for asthma. In addition, a higher proportion of individuals in the 45-64 age range in the towns were associated with a significantly decreased risk of asthma ED visits and hospitalizations. But these findings should be interpreted with caution based on the ecologic nature of the study. Most of the studies cited were hospital-based cross sectional studies or retrospective analyses of hospital administrative records.

Surprisingly, the presence of a higher percentage of non-white populations was not significantly associated with increased ED visits or hospitalizations in Connecticut after controlling for the other sociodemographic characteristics. These findings seem to support recent findings that non-genetic factors may be playing a significant role in the differences between black and white populations in the development and progression of asthma (Smith, 2005). Black race was significantly associated with a small decreased risk of ED visits (β= -
0.0071, $p < .0001$) and a miniscule increased risk of hospitalizations ($\beta=.0081, p < .0001$). Similarly, other studies have shown that controlling for income and other socioeconomic factors such as urban residence and poverty reduces or eliminates the higher asthma risks associated with black "race" in unadjusted analyses (Weiss 1992, Aligne, 2000). Some studies, however, have found a higher prevalence of asthma among black children than among white children at all levels of income, even after adjustment for such factors (Miller, 2000; Akinbami, 2002).

Further population-based and longitudinal epidemiological studies are needed to assess the role of chronic low-dose exposures to airborne pollutants as a contributor to asthma symptoms in asthmatic individuals and in the general population. Furthermore, there was a high and significant concentration of large point sources that emit high levels of $\text{PM}_{10}$ and VOC in the most densely populated areas of Connecticut that have high concentrations of poverty and non-white populations. Although it remains to be confirmed whether or not these high concentrations of pollutants in the indoor or outdoor urban setting are responsible for the high rate of ED visits and hospitalizations, the high level of toxics in urban areas may be a cause of concern (Brulle, 2006). Since environmental agents can initiate, intensify and modulate the immunologic and biologic inflammatory responses of the airway in susceptible individuals, the concentration of environmental agents such as airborne pollutants should be further investigated for their role as respiratory irritants in subpopulations (Busse, 2001). These are concerns that health agencies are beginning to address with community health investigations of asthma clusters based on asthma surveillance data at the state and local levels (White, 2002).

Of the EPA criteria pollutants, $\text{PM}_{10}$ and $\text{O}_3$ have exhibited the most evidence of associations with asthma exacerbation but the findings for the nitrogen oxides and sulfur oxides are limited (Chen, 2007). Although $\text{NO}_2$ and $\text{SO}_3$ have also been linked to asthma aggravation,
these studies have not demonstrated a clear dose dependent health risk response to increasing amounts of NO2 and SO2 except at high concentrations. In fact, some studies examining the effects of ambient level exposure to NO2 and SO2 have failed to find associations with adverse health outcomes. Evaluating the health effects of a single pollutant in ambient exposure settings is limited by three major factors. First, population-based studies are observational, thereby limiting the ability to draw definitive conclusions on causation. Second, by attempting to isolate the effect of an individual pollutant, information is lost about the potential synergistic or compounding effect of multiple pollutants. Third, the fact that the individual pollutants are rarely generated in isolation, teasing out the effect of an individual gas or particle is severely limited by the potential for confounding (Chen, 2007).

In addition to these limitations, other concerns for interpreting these findings should be mentioned such as the strong chance for ecological bias. The sources of ecological bias, omitted regional (intra-group) confounders and effect modification, are difficult to control and can lead to spurious effects (Portnov, 2007). First, asthma has a variable phenotypic expression across geographic and temporal factors and therefore, differential population selection in exposure studies has been cited as the cause of the conflicting findings in clinical and epidemiological studies. Because asthma varies in its severity, a selection bias of subjects with milder or severe forms of the disease could be responsible for the difference noted between clinical and epidemiologic studies. For instance, clinical studies of asthma are often conducted when persons are without symptoms or currently not using medication whereas some epidemiologic studies focus on acute asthma episodes requiring hospital admission. This selection bias means that the results of these studies only partially representative of all persons with asthma in the general population (Leikau, 2002).
Second, residual confounding from unmeasured confounders presents a dilemma for interpreting the results. In particular, other unmeasured sources of the criteria pollutants include mobile sources of air pollutants and indoor air pollutants and allergens (Delfino, 2002; IOM, 2000). Mobile-source emissions contribute directly to concentrations of ambient PM$_{10}$ and NO$_2$, and secondarily to O$_3$ concentrations. Spatial confounding often occurs in cross-sectional regressions due to the presence of other uncontrollable pollutants sources that share similar spatial patterns to those pollutant sources being assessed (Lipfert, 1995).

Third, differences in asthma management and insurance could be contributors to the differential rates of hospital admissions for asthma. Some population-based studies find that frequent asthma episodes can result from poor asthma management and the reliance upon rescue medications (short-acting beta agonists) rather than proper asthma monitoring and prescriptions for anti-inflammatory agents in persons with persistent asthma (Weiss, 2000; Klomp, 2008). Studies indicate that asthma can be controlled through the use of evidence-based guidelines for asthma care including patient education, appropriate diagnosis, recognition of symptoms, identification and removal of environmental allergens, and the regular inhalation of corticosteroids or short-acting beta agonists (Klomp, 2008; Pope, 2004).

In addition the collinearity of some pollutants calls into question whether or not the effects of each pollutant could be teased out from the effects of other pollutants. This was particularly of concern for PM$_{10}$ and VOCs which has a high Pearson correlation ($r=0.97$, $p<0.0001$). When two correlated pollutants are included in a regression model, their relative exposure errors influence the magnitude of the indicated associations with the dependent variable. Therefore, the indication that one pollutant has a stronger association to the health effects might be due to its smaller exposure error rather than actual heightened physiological responses to the pollutant
(Lipfert, 1995). On the other hand, using one collinear pollutant in a regression model can increase its apparent effect and statistical significance but can also conceal the parallel contributions of the other correlated pollutant (Lipfert, 1995, 2).

Still the findings support the literature that suggests that airborne pollutants may interact with various environmental, genetic and other factors at various points in the causal pathway for asthma. Although the evidence for airborne pollutants as a respiratory inflammatory agent are stronger in studies of occupational or indoor pollutants, in which there are high-dose concentrations of respiratory irritants or repeated low-dose exposures, widespread irritants from the ambient environment are of importance to environmental public health surveillance (Thacker, 1996). Due to fact that air pollution episodes have been associated with increased cardiovascular hospital admissions and mortality in time-series studies, researchers find helpful preliminary findings from ecological and cross-sectional designs (Cullinan, 2003). When exposure data are unavailable within a community, through air monitoring devices or similar apparatuses, proximity to emission sources may be used as a crude surrogate measure of exposure to air pollutants (White, 2002).

Ecological studies, or aggregate data studies, are economical for assessing exposure-disease associations among population groups defined on an ecologic or geographic basis. These types of data analysis methods have received very little attention in the scientific literature and constitute an important gap in the collection of methods pertinent to environmental epidemiologic applications (Prentice, 2004). According to Prentice et al., aggregate data studies involving the simple linear regression of disease rates or the logarithm of disease rates on average exposures and average values of potential confounding factors can often be conducted quickly and cheaply and can play a useful role in hypothesis generation.
Still more comprehensive data sources and more sophisticated data analyses typically will be required if aggregate data studies are to contribute reliably to the identification and estimation of exposure-disease associations (Prentice, 1993). Further studies are needed that can model temporal fluctuations in emissions and the patterned dispersal of emissions across a defined geographic area upon release from a particular point source (Morgenstern, 1993). Some researchers argue that, in addition to between-area comparisons, studies of within-area patterns are needed in order to further complement the field of environmental epidemiology. The usefulness of the epidemiological approach, which is designed to test differences between areas using an unexposed population as a control, can be complemented by GIS techniques that can make more robust conclusions about the within-area pattern of health effects (Dunn, 2001).

Due to the ecological and cross-sectional nature, conclusions about the appropriateness of these pollutant differences as a contributor to the differential asthma hospital admissions could not be confirmed. But the significant concentrations of pollutants in urban settings and the trend for some pollutants to be associated with a small increase in the rates of asthma hospital admissions should be further explored. It is possible that these trends could be a small reflection of the impact of other pollutants, not studied here, that contribute to asthma hospital admissions.

CONCLUSIONS
Mortality can occur for individuals with severe asthma due to inadequate emergency treatment or, in the case of underestimated asthma exacerbation, a subsequent delay in emergency department (ED) referrals for hospitalization (Klomp, 2008). Usually, however, severe asthma imposes challenges to physical activity and quality of life and increases the likelihood of ED visits and hospital admissions. ED visits and hospitalizations account for a large proportion of
the health-care cost burden of asthma, and proper asthma management of acute asthma episodes and the avoidance of asthma triggers represent an area for potential reductions in health-care costs (Gustavo, 2004).

Asthma has emerged as a major public health problem in the United States (Redd, 2002). Asthma morbidity and mortality have steadily increased since the mid-1970s but the causes of this rise are largely unknown (Delfino, 2002). Following the national trend, the 10-year asthma trend in Connecticut has been on the rise. Based on a CHIMES report from the Connecticut Hospital Association, asthma is the 8th most common reason for a resident to be seen in the ED, and the 27th most frequent diagnosis for inpatient admissions. They estimate that increasing asthma trends have implications for hospital volume increases in both the inpatient and outpatient settings related to respiratory services, additional testing in outpatient settings, increased demand for medical devices, and increased demand for long-term control medications and rescue medications (CHIMES, 2004). In fact, the direct and indirect costs of asthma in the United States were estimated to be over $12 billion during 2000, an overall 50% increase in costs since 1990 (Weiss, 2000).

The results of this ecological study find that there may be a 7% excess risk of hospital admissions attributable to PM_{10} and VOC emissions in Connecticut. Furthermore the emissions of these pollutants are concentrated in urban areas that also have increased ED visits and hospitalizations for asthma, even after controlling for sociodemographic variables. The preliminary findings of this ecological study warrant further investigation into the human health effects of criteria air pollutant levels. The large concentration of point sources that emit high levels of PM_{10} and VOC in the most densely populated areas with poverty and non-white
populations should also be further investigated for their potential contributions to differential rates of asthma hospital admissions.

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