Airborne particulate matter from primarily geologic, non-industrial sources at levels below National Ambient Air Quality Standards is associated with outpatient visits for asthma and quick-relief medication prescriptions among children less than 20 years old enrolled in Medicaid in Anchorage, Alaska

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Abstract

In Anchorage, Alaska, particulates with aerodynamic diameter \( \leq 10 \mu m \) (PM\textsubscript{10}) arise primarily from natural, geologic sources, and particulates with aerodynamic diameter \( \leq 2.5 \mu m \) (PM\textsubscript{2.5}) arise primarily from automobile emissions. The current study used a population-based time-series analysis design to evaluate the effects of daily and weekly PM\textsubscript{10} and PM\textsubscript{2.5} on respiratory health outcomes among children < 20 years of age residing in Anchorage enrolled in Medicaid. All generated estimating equations models were adjusted for season, year, weekends, temperature, wind speed, and precipitation. Relative to the days with PM\textsubscript{10} mass concentration \( \leq 13 \mu g/m^3 \), a significant 9.3% increase (RR: 1.093, 95% CI: 1.004–1.191) in the rate of outpatient visits for asthma occurred during days with PM\textsubscript{10} of 20–33 \( \mu g/m^3 \). No further dose–response occurred for days with PM\textsubscript{10} \( \geq 34 \mu g/m^3 \). A significant 18.1% increase (RR: 1.181, 95% CI: 1.010–1.381) in the rate of quick-relief medication prescriptions occurred during days with PM\textsubscript{10} of 34–60 \( \mu g/m^3 \), and a 28.8% increase (RR: 1.288, 95% CI: 1.026–1.619) occurred during days with PM\textsubscript{10} \( \geq 61 \mu g/m^3 \). Similar results for outpatient asthma visits and quick-relief medication occurred in weekly models. There were no significant associations with PM\textsubscript{2.5} in either daily or weekly models. These subtle but statistically significant associations suggest that non-industrial, geologic sources of PM\textsubscript{10} may have measurable health effects at levels below current national standards.

Keywords: Child; Air pollution; Bronchial asthma; Antiasthmatic drugs; Arctic regions

1. Introduction

Solids or liquid droplets from natural or manmade sources are known as particulate matter (PM) when suspended in airborne air. The fraction of total suspended particles with aerodynamic diameter \( \leq 10 \mu m \) (PM\textsubscript{10}) is a public health concern because these particles can be inhaled and can accumulate in the respiratory system (Environmental Protection Agency [EPA], 1990; Municipality of Anchorage, 2005).

PM is the major source of air pollution in Anchorage, Alaska, with levels periodically exceeding daily National Ambient Air Quality Standards (NAAQS) (EPA, 1990; Municipality of Anchorage, 2005). In Anchorage, seasons characterized by a combination of low levels of precipitation and lack of snow cover allow winds to aerosolize uncovered glacial silt, road dust, and other crustal materials and result in high PM\textsubscript{10}. These meteorological conditions occur primarily during the spring and fall with peak PM\textsubscript{10} levels in Anchorage during late March and...
early April, and a second peak during October and November.

In contrast to major urban centers where industrial and automobile combustion are the major sources of total suspended particles, geologic dust from natural sources appears to comprise the majority of particulates in Anchorage. In a study performed at three different cites in Anchorage between April 1984 and June 1984, investigators collected 48 samples of airborne PM with Sierra virtual impactor dichotomous samplers and sorted them for glacial till, slash burn, wood burn, peat dust, road dust, gravel pit, marine, secondary sulfate, and transportation composite in Anchorage. The investigators determined elemental compositions of reference and study samples using X-ray fluorescence. Source contributions of study samples were quantified using chemical mass balance receptor regression analysis, comparing characteristics of study samples to reference samples. The results implied that reference samples explained almost 100% of the composition of airborne particles. The coarse fraction comprised 80% of the overall particle mass. Crustal materials (soil, road dust, glacial till) comprised 90–98% of PM2.5–10. Of the fine fraction, 64–85% derived from crustal materials, 10–15% from transportation, and 4–10% from secondary sulfates. In another study, investigators collected 18 PM10 samples from 1989 to 1994 in Anchorage (Municipality of Anchorage, 1985). Investigators created reference samples for PM10 by using X-ray fluorescence. Source contributions of study samples were quantified using chemical mass balance receptor regression analysis, comparing characteristics of study samples to reference samples. The results implied that reference samples explained almost 100% of the composition of airborne particles. The coarse fraction comprised 80% of the overall particle mass. Crustal materials (soil, road dust, glacial till) comprised 90–98% of PM2.5–10. Of the fine fraction, 64–85% derived from crustal materials, 10–15% from transportation, and 4–10% from secondary sulfates. In another study, investigators collected 18 PM10 samples from 1989 to 1994 in Anchorage (Municipality of Anchorage, 1994). Each sample underwent microscopic quantitative assemblage analysis, determining the source of particulates by size distribution and surface characteristics. "Natural" particulates, including plant spores, magnetite, charcoal, plant fibers, crystalline mineral, pollen, diatoms, and epithelial materials, comprised on average 6.2% (standard deviation 19.8%) of the PM10’s of each sample. Volcanic ash, including magnetite, black glass, feldspars, and Pyreens, comprised on average 28.3% (standard deviation 29.5%) of each sample. Road sand, including quartz, shell fragments, limestone, mica, amphiboles, and garnet, comprised on average 23.3% (standard deviation 20.2%) of each sample. Traffic debris comprised the largest component (mean 42.2%, standard deviation 28.7%) of each sample. Although the majority (77%) of traffic debris was anthropogenic in origin and included substances such as tire wear, metal, cenospheres, soot, and asphalt concrete, this fraction corresponds to only 32.3% of total PM10. Worn and weathered volcanic minerals and other weathered crustal materials comprised the remainder (23%) of traffic debris. A study of samples corresponding to local volcanic activity revealed that 87–95% of PM10 was attributed to volcanic ash when Mt. Spurr (75 miles from Anchorage) erupted during August 1992. The ash lingered, comprising up to 24% of PM10 during 1994. More recently, data collected at different locations during the winters of 1999–2004 demonstrated a correlation between carbon monoxide (CO) and PM2.5, suggesting fine particulates are attributable to motor vehicle emissions during the cold season (Municipality of Anchorage, 2005).

Several studies have determined that increased ambient PM10 and PM2.5 levels are associated with decreased pulmonary function, increased respiratory symptoms, increased visits to health care providers and emergency rooms for asthma, and deaths from respiratory and cardiovascular causes across different age groups, sex, and race/ethnicity (Klot et al., 2002; Zhang et al., 2002; Pope et al., 1991; Schwartz et al., 1993; Mortimer et al., 2002; Dockery et al., 1993). However, industrial and not geologic sources were responsible for elevated PM10 and PM2.5 in these studies and thus the results may not be generalizable to Anchorage and other mid-size communities with little industrialization. Previous studies have evaluated the association between PM10 and respiratory health outcomes in Anchorage (Gordan et al., 1996; Choudhury et al., 1997). However, data from these studies were collected shortly after the eruption of Mt. Spurr resulting in hourly PM10 level peaks over 3000 µg/m³ (Municipality of Anchorage, 2005; Gordan et al., 1996; Choudhury et al., 1997). Additionally, this study did not determine the effects of PM2.5, did not investigate more severe, inpatient health outcomes, and did not include one of the most susceptible subpopulations, children without private or family employer-based health insurance. The objective of the current study was to determine the effects of PM10 and PM2.5 particulate matter on inpatient and outpatient respiratory health outcomes among the Anchorage Medicaid-enrolled population age less than age 20 years.

2. Methods

2.1. Study site

Anchorage is Alaska’s largest city, with approximately 240,000 residents. It is bounded by mountains and ocean with an average temperature during January (the coldest month) of ~9.4 °C and during July (the warmest month) 14.4 °C (Climate-zone.com, 2006; National Oceanic and Atmospheric Administration [NOAA], 2005). The average precipitation during March (the driest month) is 1.8 cm and during September (the wettest month) 6.9 cm (Climate-zone.com, 2006; NOAA, 2005).

Alaska has 41 historically active volcanoes. From 1998 to 2003, there were 10 explosive or possible eruptions of seven volcanoes. None were reported to have released ash onto Anchorage (Geophysical Institute of the University of Alaska at Fairbanks, United States Geologic Survey, 2006).

2.2. Study design

We designed a population-based, time-series study to evaluate the association between daily PM and the number of asthma-related and lower respiratory infection claims billed to Medicaid. The unit of analysis was the date or the week. The study was limited to Anchorage residents because environmental testing data for the remainder of the state were not available. We limited participants to those <20 years of age because of
concern that medications used to treat asthma in children and young adults might be used for other conditions in older persons, such as emphysema or chronic obstructive pulmonary disease. The study was limited to the years 1999–2003 because before this, some providers billed Medicaid in bulk rather than by individual.

2.3. Health outcomes data sources

To create the database of daily-billed asthma-related outcomes, we modified a methodology that has been previously reported (Gessner, Neeno, 2005; Gessner, 2003). In brief, a file was constructed containing information on all persons less than 20 years of age enrolled in Medicaid at some time during January 1, 1999 through June 20, 2003. An outcomes file was created that contained all providers, inpatient facility, and outpatient clinic approved billing claims for all outcomes of interest (see Case definitions below). A separate file contained data on asthma medications. From these databases, we created another database with one record for each day during the 4-year study period. For each record, variables were created recording the number of approved billings for each outcome of interest.

2.4. Operational definitions of health outcomes

**Asthma.** An approved claim for any asthma-related care from an outpatient or inpatient facility based on International Classification of Diseases, 9th Revision (ICD-9) codes 493.0–493.9, the standard codes for asthma. Asthma-related hospitalization included any approved claim for which asthma was recorded as a discharge diagnosis.

**Inhaled quick-relief medication:** An approved claim for a short-acting beta agonist or ipratropium bromide of any brand, including generic. These are commonly referred to as emergency inhaler medications.

**Steroid medication:** An approved claim for any inhaled corticosteroid. Oral steroids were not included because of their frequent indication for diseases other than asthma and the assumption that any child receiving oral steroids would also receive other asthma medications.

**Lower respiratory illness:** An approved claim for ICD-9 code 466.1 (bronchiolitis), 466.0 (bronchitis), 480–487 (pneumonia and influenza), or 510–511 (empyema and pleurisy).

2.5. Environmental data sources

We obtained outdoor airborne suspended PM data from the Municipality of Anchorage, Department of Health and Human Services (DHHS), Division of Environmental Services. DHHS uses Anderson-head PM10 samplers to collect PM10 samples and Rupprecht and Patashnick Partisol 2000 samples to collect PM2.5. Gravimetric analysis is used to calculate both total 24-h PM10 and PM2.5 mass for each day, adjusted for influence of single daily measurements with abnormally high (or low) values. The analysis by week allowed simultaneous inclusion and adjustment of PM2.5 and PM10 under the premise that missing values for a given day would have a small impact on the weekly median. Analysis by week also minimized the lag effect documented in other studies whereby a spike in daily PM can influence health outcomes on subsequent days (Pope et al., 1991; Schwartz et al., 1993; Mortimer et al., 2002; Gordin et al., 1996; Choudhury et al., 1997).

Serial correlation is an issue in time-series data in which the same measurement is repeated throughout time (Stokes et al., 1995). We used generalized estimating equations (GEE) for multivariable modeling because this method provides consistent estimators for regression coefficients and their variances under weak assumptions about the actual correlation structure between repeated measurements (Stokes et al., 1995). The distribution of the health outcome variables was set as Poisson, and over dispersion was corrected by setting the scale to deviance. Models were offset to the natural logarithm of the number of Medicaid enrollees <20 years for the appropriate year. Correlation between daily or weekly health outcome measurements within each season of each year was corrected assuming an exchangeable working correlation matrix. All daily models were adjusted by minimum temperature, wind speed, precipitation, and week-end status. Weekly models were adjusted by weekly median of daily minimum temperature, precipitation, wind speed, PM10, and PM2.5. Incidence density (rate ratios), and 95% confidence intervals were obtained by exponentiating the regression coefficients and standard errors (Stokes et al., 1995).

To determine if respiratory problems occurred below the NAAQS standard of 150 μg/m3, daily models with significant associations between the health outcome and PM10 were run excluding those days with PM10 ≥150 μg/m3 (EPA, 1990). To determine the dose–response effect, both daily and weekly models with significant PM10 associations were rerun using all available data substituting a categorical PM10 variable broken into five categories for the continuous variables. The PM10 categories corresponded to quartiles for daily measurements or weekly medians. Because the distributions of daily PM10 and weekly PM10 medians had a skew to the right, with a long tail of very high values well above typical daily and weekly values, we divided the highest quartile into two categories: one ≤60 μg/m3 and one >60 μg/m3. PM10 levels >60 μg/m3 occurred for 8.4% of daily measurements and 5.2% of weekly medians. Datasets were created with SPSS, 11.0 (Chicago, IL) and analyses were performed with SAS, 8.0 (Cary, NC).

2.7. Analysis

We compared asthma, lower respiratory infection, and medication outcomes by PM. We ran two sets of analysis, one with date and one with week as the unit of analysis. In both sets of models we assume that health events are followed relatively quickly by physician visits (urgent care or emergency department if not a regular provider) since if a person had completely recovered they likely would cancel an appointment at a later date. We make the same assumption for getting a prescription filled. Because the data in the Medicaid file is the date of service and not the billing date, analyses based on the day allowed us to determine the near instantaneous effect of PM on the outcome variables. However, inclusion and adjustment of both PM10 and PM2.5 as independent variables was not possible because simultaneous measurements were available for only a portion (18.1%) of days leading to problems with small sample size.

Analyses based on the week was performed by obtaining weekly totals for each health outcome variable and using weekly medians for each independent variable. The median was chosen as the appropriate measure of central tendency because it is less susceptible than the mean to the influence of single daily measurements with abnormally high (or low) values. The analysis by week allowed simultaneous inclusion and adjustment of PM2.5 and PM10 under the premise that missing values for a given day would have a small impact on the weekly median. Analysis by week also minimized the lag effect documented in other studies whereby a spike in daily PM can influence health outcomes on subsequent days (Pope et al., 1991; Schwartz et al., 1993; Mortimer et al., 2002; Gordin et al., 1996; Choudhury et al., 1997).

Datasets were created with SPSS, 11.0 (Chicago, IL) and analyses were performed with SAS, 8.0 (Cary, NC).
2.8. Ethical considerations

This study involved linkage of existing legally authorized administrative databases housed at the Alaska Department of Health and Social Services. No novel data were obtained. Under these circumstances of routine public health evaluation, institutional review board approval and informed consent were neither sought nor obtained.

3. Results

A total of 21,260 children between the ages of 0 and 19 years were enrolled in Medicaid during 1999, 23,915 in 2000, 25,616 in 2001, 27,157 in 2002, and 24,775 in 2003. During the study period, there were 11,037 approved claims for outpatient asthma, 280 for inpatient asthma, 19,423 for outpatient lower respiratory tract infection, 711 for inpatient lower respiratory tract infection, 6090 for an inhaled steroid. Mean daily and weekly total outpatient visits for asthma and lower respiratory infections were higher than corresponding inpatient admissions (Table 1). The monthly average of daily mean asthma, inhaled quick-relief medication, and lower respiratory outcome counts showed some variation with peaks during the winter and a secondary peak in asthma and inhaled quick-relief medication use during the wet month of September (Fig. 1).

The mean monthly PM\textsubscript{10} level showed substantial variation with a major peak during spring and a lesser peak during fall while PM\textsubscript{2.5} showed much less variation (Fig. 2). Data were missing for 863 (52.6%) days for PM\textsubscript{10} and 1,026 (62.5%) for PM\textsubscript{2.5} (Table 1). When collapsed into 235 weeks, medians were missing for 3 (1.3%) weeks for PM\textsubscript{10} and 5 (2.1%) for PM\textsubscript{2.5}. Daily PM\textsubscript{10} measurements were skewed to the right with a maximum of 421 m\textsuperscript{3} and an interquartile range of 12–33 m\textsuperscript{3}. Weekly median PM\textsubscript{10} had a similar but less dramatic skew with a maximum of 116 m\textsuperscript{3} and an interquartile range of 13.5–30 m\textsuperscript{3}. PM\textsubscript{10} was >60 m\textsuperscript{3} for 65 (8.4%) days, ≥100 m\textsuperscript{3} for 12 (1.5%) and ≥150 m\textsuperscript{3} for 3 (0.4%) days. Weekly median PM\textsubscript{10} levels were >60 m\textsuperscript{3} for 12 (5.2%) weeks, and ≥100 m\textsuperscript{3} for 2 (0.9%). Daily PM\textsubscript{10} levels were weakly correlated to daily PM\textsubscript{2.5} (ρ = 0.25, P<0.01, n = 297). Weekly median PM\textsubscript{10} levels were not significantly correlated with median PM\textsubscript{2.5} (ρ = 0.08, P = 0.21).

Using GEE to adjust for serial correlation, season, year, weekend, minimum temperature, wind speed, and precipitation, a 10 m\textsuperscript{3} increase in daily PM\textsubscript{10} was significantly associated with a 0.6% increase in outpatient asthma visits (RR: 1.006, 95% CI: 1.001–1.013) and a 1.8% increase in inhaled quick-relief medication prescriptions (RR: 1.018, 95% CI: 1.006–1.030) (Table 2). Removing days with PM\textsubscript{10} ≥150 m\textsuperscript{3} did not change the association with asthma (RR: 1.014, 95% CI: 1.004–1.023) but increased the magnitude of the association with inhaled quick-relief medication prescriptions (RR: 1.030, 95% CI: 1.002–1.060). When the categorical PM\textsubscript{10} variable was substituted for the continuous variable in the outpatient asthma model, there were no notable changes in the dose–response relationship beyond a
significant 9.3% increase (RR: 1.093, 95% CI: 1.004–1.191) that occurred at the third PM10 quartile (PM10: 20–33 \( \mu g/m^3 \)) (Fig. 3). In the corresponding model for prescriptions of inhaled quick-relief medication, a significant 18.1% increase (RR: 1.181, 95% CI: 1.010–1.381) in prescriptions occurred for PM10 between 34 and 60 \( \mu g/m^3 \) and 28.8% (RR: 1.288, 95% CI: 1.026–1.619) for PM10 61 \( \mu g/m^3 \) (Fig. 4). Daily PM10 was not significantly associated with outpatient or inpatient lower respiratory infections, inpatient asthma, or the number of inhaled steroid prescriptions. After adjusting for serial correlation, season, year, weekend, minimum temperature, wind speed, and precipitation, a 5\( \mu g/m^3 \) increase in daily PM2.5 was not significantly associated with any outcome measurement (Table 2).

Using fully adjusted GEE for weekly health outcomes, a 10\( \mu g/m^3 \) increase in weekly median PM10 was significantly associated with a 2.1% increase (RR: 1.021, 95% CI: 1.004–1.038) in outpatient asthma visits and a 5.7% (RR: 1.057, 95% CI: 1.037–1.077) increase in inhaled quick-relief medication (Table 2). When the categorical PM10 variable was substituted for the continuous variable corresponding to median weekly PM10 quartiles, a significant 8.1% decrease (RR: 0.919, 95% CI: 0.849–0.993) in the rate of outpatient visits for asthma was observed at the second quartile (PM10: 13.5–20 \( \mu g/m^3 \)) (Fig. 5). No significant association occurred at the third quartile or between PM10 of 31 and 60 \( \mu g/m^3 \). A non-significant 11.6% increase (RR: 1.116, 95% CI: 0.979–1.271) occurred at 61 \( \mu g/m^3 \). In the corresponding model for inhaled quick-relief medication, a significant 18.0% increase (RR: 1.180, 95% CI: 1.040–1.034) occurred at PM10 between 31 and 60 \( \mu g/m^3 \), and a 40.9% increase (RR: 1.409, 95% CI: 1.192–1.665) at PM10 >61 \( \mu g/m^3 \) (Fig. 6). Weekly median PM10 levels were not significantly associated with outpatient or inpatient lower respiratory infections, inpatient asthma, or the

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<th>Outcome</th>
<th>Analysis by day</th>
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<td>PM10</td>
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<td>RR 95% CI</td>
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<td>Outpatient lower respiratory infection</td>
<td>1.001 (0.987, 1.015)</td>
<td>0.952 (0.907, 1.001)</td>
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<td>Inpatient asthma</td>
<td>1.003 (0.922, 1.091)</td>
<td>0.936 (0.798, 1.098)</td>
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<tr>
<td>Inpatient lower respiratory infection</td>
<td>1.015 (0.978, 1.053)</td>
<td>0.919 (0.823, 1.027)</td>
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<td>Inhaled steroid prescriptions</td>
<td>1.006 (0.996, 1.011)</td>
<td>0.988 (0.902, 1.083)</td>
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<td>Quick-relief medication</td>
<td>1.018 (1.006, 1.030)</td>
<td>0.962 (0.901, 1.028)</td>
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*Analyses by day are further adjusted for week-ends. PM10 and PM2.5 are not entered into the same model.

*Analyses by week are simultaneously adjusted for PM10 and PM2.5.
number of inhaled steroid prescriptions. A 5 μg/m^3 increase in weekly median PM_{2.5} was not significantly associated with inpatient or outpatient asthma, inpatient or outpatient lower respiratory tract infections, or prescriptions of inhaled steroids or inhaled quick-relief medication (Table 2).

4. Discussion

We found that daily and weekly median PM_{10} levels in Anchorage exhibited significant, dose–response relationships with prescriptions of inhaled quick-relief medication. Although an association was also found between PM_{10} levels and outpatient asthma, no clear dose–response was observed. The observed daily pattern, with no continued increase in risk after PM_{10} > 20 μg/m^3, may represent a statistical artifact from an uncontrolled confounding variable such as pollen count or the saturation of a subtle effect, with threshold dose information lost when PM_{10} levels were collapsed into categories.

In our study, the lack of significant associations between PM and corticosteroids was expected because inhaled steroids are used primarily as maintenance medications for chronic asthma rather than rescue medications. Furthermore, the lack of significant association with inpatient asthma suggests that unmeasured risk factors such as exposure to cigarette smoke, poor indoor air quality, and respiratory infection are more important determinants for severe asthma exacerbations than PM in this population.

With the exception of natural events such as volcanic eruptions and windstorms, the highest PM_{10} mass concentrations occur near busy roadways with levels decreasing as the distance from the roadway increases (Municipality of Anchorage, 2005). Because the majority of PM_{10} data during the study period were collected near a busy street in Anchorage and because much of Anchorage’s housing is located at a distance from major roadways, our sub-analyses that uses specific categories of PM_{10} mass concentration likely overestimates the PM_{10} exposure of our study population. Thus, the increased occurrence of outpatient asthma visits and quick-relief medication likely occur at PM_{10} levels lower than those depicted in Figs. 3–6.

**Fig. 5.** Rate ratios 95% confidence interval for prescriptions of inhaled quick-relief medications by median weekly PM_{10}, adjusted for year, season, serial time trend, temperature, wind speed, precipitation, and weekly median PM_{2.5} among Medicaid patients ages 0–19 years residing in Anchorage, Alaska, January 1999–June 2003, n = 225 weeks. Particulate matter data displayed has been pooled from all sampling sites.

**Fig. 6.** Rate ratios 95% confidence interval for outpatient visits for asthma by median weekly PM_{10}, adjusted for year, season, serial time trend, temperature, wind speed, precipitation, and weekly median PM_{2.5} among Medicaid patients ages 0–19 years residing in Anchorage, Alaska, January 1999–June 2003, n = 225 weeks. Particulate matter data displayed has been pooled from all sampling sites.
coincided with the eruption of a nearby volcano (Gordian et al., 1996; Choudhury et al., 1997). Moreover, although the authors filtered out the effects of anomalously high PM$_{10}$ concentrations caused by the volcanic eruptions with mathematical models, the overall daily mean PM$_{10}$ concentration was higher (41.5 $\mu$g/m$^3$ overall, 37 $\mu$g/m$^3$ for week-ends, and 48 $\mu$g/m$^3$ for week-days) than during the time period of the present study (27.6 $\mu$g/m$^3$ overall) (Gordian et al., 1996; Choudhury et al., 1997).

Despite their differences, the available studies are consistent in their indication that the NAAQS level of 150 $\mu$g/m$^3$ for PM$_{10}$ underestimates the threshold at which measurable health effects occur. Additionally, the Environmental Protection Agency Clean Air Scientific Advisory Committee has recently proposed abolishing PM$_{10}$ standards for non-urban communities based on the assumption that urban and industrial sources of PM$_{10}$ have a substantial effect on health but geologic sources do not (EPA, 2005). Our data and previous reports from Alaska indicate that, at least in arctic environments, non-urban PM has a measurable effect on health and thus that monitoring will serve a useful public health function.

Unlike PM$_{10}$, we found no association between health outcomes and PM$_{2.5}$. Recent studies suggest that PM$_{2.5}$ levels have a greater potential for cardiopulmonary morbidity and mortality than PM$_{10}$ because smaller particles are more easily deposited in the distal airways (EPA, 1990; Klot et al., 2002; Dockery et al., 1993). A recent European study found PM$_{2.5}$ and ultrafine particles to have stronger, more consistent associations with increased use of inhaled quick-relief medication and corticosteroid medications than the coarse fraction of particulates (PM$_{2.5-10}$). However, the course fraction of particles (daily mean PM$_{2.5-10}$ of 10.3 $\mu$g/m$^3$) and the ambient levels of PM$_{2.5}$ (daily mean of 30.3 $\mu$g/m$^3$) was high compared to the present study (daily mean PM$_{2.5}$ of 6.1 $\mu$g/m$^3$ and data previously collected in Anchorage (PM$_{2.5-10}$ is 80% of total suspended particles) (Klot et al., 2002; Municipality of Anchorage, 1985). By contrast, our results are consistent with the Four Chinese City Study, which found larger particles (total suspended particles, PM$_{10}$, PM$_{2.5-10}$) to be better predictors of respiratory symptoms among children than PM$_{2.5}$, despite the fact that mass concentrations for all particle sizes in the Chinese study were extremely high (92 $\mu$g/m$^3$ for PM$_{2.5}$, 59 $\mu$g/m$^3$ for PM$_{2.5-10}$, 151 $\mu$g/m$^3$ for PM$_{10}$ and 356 $\mu$g/m$^3$ for total suspended particles) (Zhang et al., 2002).

Our study is limited by the fact that we did not directly determine the source (anthropogenic versus natural) of the PM in our study. Rather we assume that the bulk of PM$_{10}$ was not anthropogenic based on the results of previous studies (Municipality of Anchorage 1985, 1994, 2005). The methods used in these studies whereby source apportionment was determined by mathematical modeling and surface morphology were inferential in nature and can be inexact.

Our study is limited by the fact that our GEE models do not directly adjust for airborne pollen concentrations or other pollutants such as ozone, CO, sulfur dioxides, volatile organic compounds, and nitrogen dioxide, which were associated with asthma outcomes in other studies (Klot et al., 2002; Mortimer et al., 2002; White et al., 1994; Cody et al., 1992; Bates, Szito, 1987; Bates et al., 1990). However, sulfur dioxide measurements in Anchorage from the 1980s were consistently low (daily average of 9 ppb compared to the NAAQS standard of 140 ppb), prompting the discontinuation of monitoring (Municipality of Anchorage, 2005). No monitoring of nitrogen dioxide (primarily from fuel combustion) occurs in Anchorage; however, levels likely are similar to the US as a whole and all areas of the US that monitor NO$_2$ have been in compliance with NAAQS during the study period with the exception of Los Angeles (Municipality of Anchorage, 2005; EPA, 1997a,b, 2006). Ozone is unlikely to play a substantial role since temperature and light intensity in Anchorage (latitude 61° N) do not favor ground level ozone formation. Ozone was monitored in Anchorage from April through December 1983 and from April through September 1985 at two different locations. The highest 8-h ozone measurement during all time periods was 36 ppb, less than half the NAAQS standard of 80 ppb (Municipality of Anchorage, 2005). During winter months, cold air inversion can lead to levels of volatile organic compounds (such as benzene > 5 ppm) and CO > 9 ppb (the 8-h NAAQS standard). Both volatile organic compounds and CO are primarily from automobile emissions, and have been highly correlated ($R^2 = 0.95$) in data obtained from hundreds of measurements at three different locations in Anchorage during April of 1993 through April of 1994. Data collected at different locations during the winters of 1999–2004 demonstrated a correlation ($R^2 = 0.63$) between CO and PM$_{2.5}$ based on hundreds of measurements (Municipality of Anchorage, 2005). Although year-round monitoring of CO and volatile organic compounds was not available for the present study, the high correlations between CO and volatile organic compounds and between CO and PM$_{2.5}$ and the inclusion of PM$_{2.5}$ in weekly GEE models provided limited control of the potential confounding effects of CO and volatile organic compounds.

We were unable to control for personal risk factors for respiratory disease such as sex, race, personal and parental cigarette smoking, indoor air quality, and indoor allergens. However, the omission of these variables would not confound our results provided the prevalence of these risk factors remained stable in our study population throughout the study period.

PM$_{10}$ levels in Anchorage and potentially elsewhere in the arctic correlate with asthma outcomes, including at levels well below the current daily NAAQS standard of 150 $\mu$g/m$^3$. This subtle but significant association combined with data from previous studies should prompt the Environmental Protection Agency to reassess its current standard and consider continued support of PM$_{10}$.
monitoring in non-industrial areas where geologic activity, such as seasonal movement of glacial silt and high winds, leads to high PM$_{10}$ levels.

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Ethical considerations. This study involved linkage of existing legally authorized administrative databases housed at the Alaska Department of Health and Social Services. No novel data were obtained. Under these circumstances of routine public health evaluation, institutional review board approval and informed consent were neither sought nor obtained.

References