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The relationship of high $PM_{2.5}$ days and subsequent asthma-related hospital encounters during the fireplace season in Phoenix, AZ, 2008–2012

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Abstract Exposure to particulate matter less than 2.5 μm in diameter ($PM_{2.5}$) exacerbates asthma and increases mortality. In Phoenix, AZ, the highest $PM_{2.5}$ values frequently occur during the winter fireplace season and air quality health standards are often exceeded during the Christmas and New Year's holidays. It was clear that enhanced messaging was needed by air quality and public health authorities to discourage biomass fires (BMF) on days when unhealthful levels of pollution were likely to be caused by that activity. Demonstrating adverse health outcomes would bolster this effort. We conducted this study to evaluate associations between elevated $PM_{2.5}$ exposures during the fireplace season and asthma-related hospital admissions in Phoenix; days with average $PM_{2.5} > 35\ \mu g/m^3$ were categorized as elevated $PM_{2.5}$ exposure. We used hospital discharge data to identify patients with an asthma-related hospital encounter and who lived within an 8-km radius of a $PM_{2.5}$ monitor. To estimate the risk of a hospital encounter following an elevated $PM_{2.5}$ event, we used generalized estimating equations, specified with a Poisson distribution, and exposure lags of 0–3 days. Controlling for influenza, temperature, humidity, rain, and year, these analyses generated elevated estimates of emergency department visit risk among adults on lag days 2 (relative risk [RR] 1.19; 95 % CI 1.06, 1.34) and 3 (RR 1.20, 95 % CI 1.05, 1.37). Elevated $PM_{2.5}$ was not associated with hospital encounters among children. Our findings suggest that adults may be at elevated risk of asthma-related hospital encounters during the fireplace season.

Keywords Air pollution · Air quality · Asthma · Biomass burning · Epidemiology · Respiratory health

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Introduction

Asthma is chronic health condition of major importance in the USA. The prevalence of asthma has increased from 7.3 % of the population in 2001 to 8.4 % in 2010 and put increasing numbers of people at risk of an asthma-related hospital encounter (Akinbami et al. 2012). In 2011, 18.9 million adults and 7.1 million children in the USA experienced asthma (Schiller et al. 2012; Bloom et al. 2012). As a first-listed diagnosis in US hospital in-patient (IP) records, asthma accounted for nearly half a million IP hospital stays and over 1.7 million emergency department (ED) visits (CDC/NCHS 2010a, 2010b), with medical costs exceeding $51 billion in 2007 (Barnett and Nurmagambetov 2011). In Maricopa County, Arizona, a first-listed diagnosis of asthma accounted for 4831 IP stays, hospital billing charges over $580 million, and nearly 60,000 hospitalization days in 2011 alone (Maricopa County Department of Public Health-Office of Epidemiology 2013). In addition, asthma was the underlying cause of 57 deaths (Maricopa County Department of Public Health-Office of Epidemiology 2013).

To date, extensive public health research provides evidence that exposure to particulate matter less than 2.5 μm in diameter ($PM_{2.5}$), one of the criteria air pollutants for which the US National Ambient Air Quality Standards (NAAQS) are in

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place, affects respiratory health (U.S. EPA 2010). In order to address health risks of exposure to $PM_{2.5}$, the US Environmental Protection Agency (EPA) first implemented NAAQS for $PM_{2.5}$ in 1997 and subsequently lowered the exceedance thresholds in 2006 and 2012; currently, $PM_{2.5}$ NAAQS are 35 μg/m^3 for 24-h exposure and 12 μg/m^3 for annual exposure (U.S. EPA 2013). Existing $PM_{2.5}$ exposure research provides evidence of a causal association between $PM_{2.5}$ exposure and numerous cardiopulmonary effects (Ito et al. 2007; Pope et al. 2002; U.S. EPA 2010; Anderson et al. 2012). Major anthropogenic $PM_{2.5}$ emission sources include certain industrial and combustion processes (e.g., power plants, motor vehicles, and residential biomass combustion).

The Phoenix metropolitan area of Maricopa County, the region in which this study was conducted, is geographically unique and its characteristics affect the presence of particulate pollution. The region is in arid, sub-tropical latitudes and has predominantly high atmospheric pressure with light winds and weak atmospheric circulation. This prevailing lack of strong atmospheric circulation, in combination with Phoenix's location in the Salt River Valley, impedes the dispersion of pollutants (Ellis et al. 1999, 2000). The pollutant-trapping topography of the Phoenix region is compounded by wintertime atmospheric stagnation and temperature inversion events that occur frequently in the southwestern deserts. These temperature inversions can create stable atmospheric conditions up to 20 m (at sunset) to 100 m (at sunrise) in altitude (Pardyjak et al. 2009), which serve to trap pollutants near their sources. In Maricopa County, the $PM_{2.5}$ 24-h exposure standard is exceeded occasionally, especially during the late fall through the mid-winter period, though at the time of this report, the County was in regulatory attainment of the $PM_{2.5}$ NAAQS (MCAQD 2013a).

In the central Phoenix area, many homes are located in older neighborhoods that contain wood-burning indoor and outdoor fireplaces; due to the clean-burning fireplace ordinance enacted in 1998,[1] newer neighborhoods located in suburban areas of Phoenix often either lack indoor fireplaces or use clean-burning fuel (MCAQD 2013b). The "official" fireplace season, a time period defined during the first attempts in the early 1990s to regulate residential wood-burning in Maricopa County (Maricopa County Environmental Services Department 1995), extends from October through February, corresponding to the region's relatively short and mild winter season. In Maricopa County, the highest $PM_{2.5}$ levels measured and most exceedances of the NAAQS usually occur during this time, and nearly all of the NAAQS exceedances occur on or around Christmas and New Year's Day (MCAQD 2013a). Despite wood-burning restrictions, referred to as "no-burn days," analyses of long-term chemically speciated $PM_{2.5}$ data suggest that biomass burning still takes place (ADEQ 2001). Chemical markers of biomass burning are significantly higher on weekends and holidays, as are total $PM_{2.5}$ concentrations, which strongly suggests biomass fires (BMF) as the primary area source. Source apportionment modeling studies also implicate BMF as the primary source of $PM_{2.5}$ during the fireplace season (Domsky 2013; Maricopa County Air Quality Department 2014).

Despite evidence that particulate air pollution, especially $PM_{2.5}$, exacerbates asthma symptoms and causes acute asthmatic episodes (Antó 2012; Laumbach and Kipen 2012; Tecer et al. 2008), the relationship between particulates generated by BMF and asthma is unclear (Naeher et al. 2007). Evidence of a link between cooking over BMF and self-reported asthma is equivocal (Mishra 2003; Barry et al. 2010; Po et al. 2011). A study on the correlation between exposure to $PM_{2.5}$ from wildfire smoke and asthma-related hospital admissions in Southern California reported that increased $PM_{2.5}$ concentrations were associated with increased numbers of hospital encounters among adults, but not among children aged 4–18 years (Delfino et al. 2009). Another study found that wildfire PM_{10} was associated with an increase in adult hospital encounters on the same day of exposure and a slight decrease in admissions for childhood asthma at 3 days later (Morgan et al. 2010).

Despite the prohibitions on burning set by Maricopa County Air Quality Department and multiple methods of broadcast "no-burn day" notifications, $PM_{2.5}$ concentrations consistently spiked well above the NAAQS on those days, in large part, due to BMF. One of the primary objectives of conducting this research was to enhance messaging by air quality and public health authorities to discourage BMF on days when unhealthful levels of pollution were likely to be caused by that activity. To evaluate the extent to which elevated $PM_{2.5}$ exposures from BMF during the fireplace season in Maricopa County may affect local asthma-related hospital encounters, we conducted an epidemiologic study of the association between exceedances of the ambient $PM_{2.5}$ NAAQS in central Phoenix and asthma-related ED and IP hospital encounters in Maricopa County, Arizona. Using air quality data collected during the fall and winter fireplace seasons of 2008 through 2012 and asthma-related hospital discharge data, we present risks of an asthma-related hospital encounter for children and adults following days with elevated $PM_{2.5}$.

Methods

Study characteristics

The study was based in Phoenix, Arizona; we identified the geographic area of our study using the locations of four official

[1] Arizona Revised Statutes §§9–500.16 and 11–875 requires all homes in the Phoenix air pollution control area built after 1998 to comply with clean-burning fireplace standards, e.g., EPA-certified permanently installed gas or electric log inserts.

$PM_{2.5}$-monitoring stations (Fig. 1), as they were the only stations with a sufficient historical record of daily sampling. We used 8-km buffers around each monitoring station (Dimitrova et al. 2012), with overlap being combined, to create the boundaries shown in Fig. 1. Thus delineated, the study area includes the urban core of Phoenix, consisting mostly of residential (40 %) and commercial (35 %) parcels; industrial (5 %), vacant (17 %), and agricultural (3 %) make up the remaining parcels.

The study was confined to the middle of the fireplace season from November 1 through January 31, 2008–2012, for a total of four seasons. The years 2008–2012 were chosen due to the availability of continuous $PM_{2.5}$ data, as well as continuity among diagnoses in the Arizona hospital discharge data.

Data sources

We obtained hospital discharge data from the Arizona Department of Health Services for all ages both for IP stays and ED visits, collectively referred to in this study as hospital encounters. Hospital discharge data in Arizona contain one primary diagnosis code and up to 24 secondary diagnosis codes. Asthma-related hospital encounters were considered to be any record that contained the ICD-9-CM code 493 in any of the 25 diagnostic codes in each record. Additional codes for asthma were used in an attempt to capture all potential cases of asthma, but upon review each record also contained the code 493. Additional information extracted from the hospital discharge data included age, sex, day of week of admission, date of admission, type of admission (IP or ED), influenza case load, and patient's residential address.

We categorized patient age as child (0–19 years) or adult (20 years or older), based on the age reported at the time of the hospital encounter. We categorized the day of admission as weekend (Saturday and Sunday) or weekday (Monday through Friday), based on evidence that hospital encounters

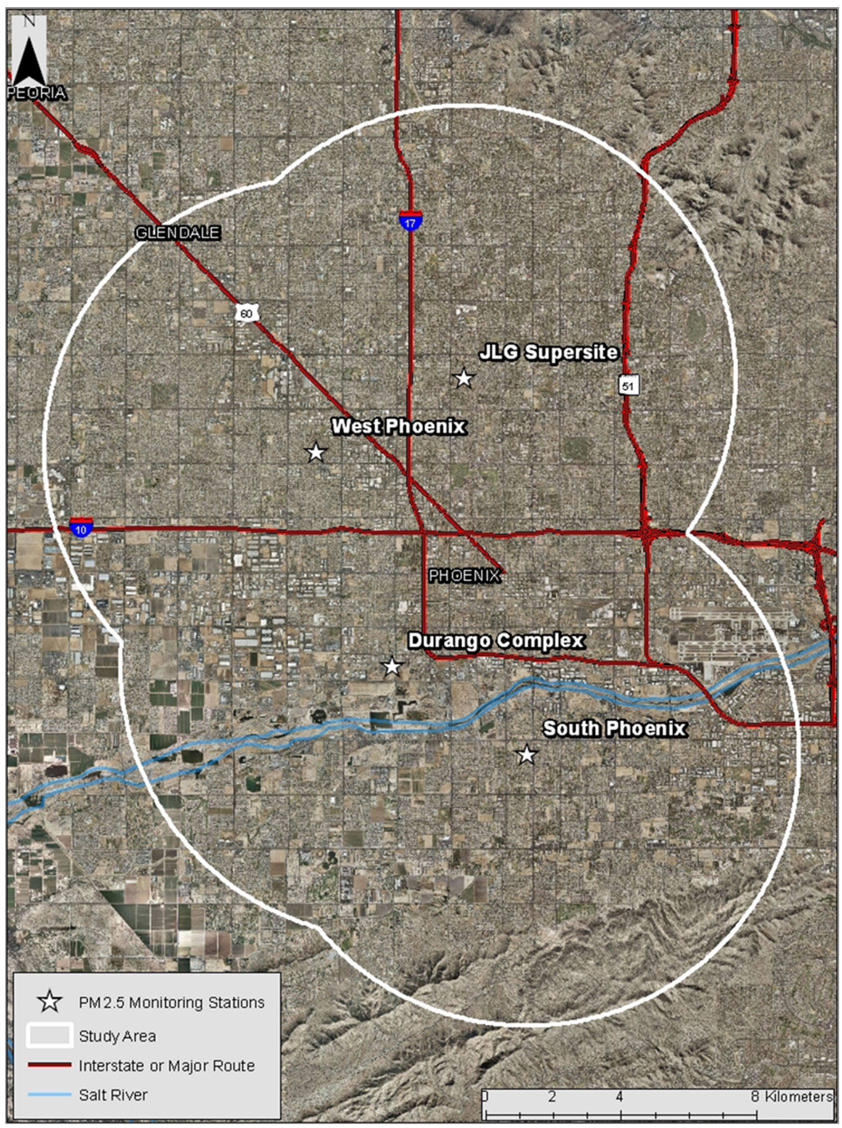

Fig. 1 Aerial photograph of the Phoenix, AZ, urban area showing the location of the study area and $PM_{2.5}$-monitoring stations. The Durango Complex, South Phoenix, and West Phoenix stations are operated by the Maricopa County Air Quality Department; the JLG Supersite station is operated by the Arizona Department of Environmental Quality

differ by weekend versus weekday status (Ryan et al. 2010; Schwartz et al. 1996).

Influenza cases were also extracted from hospital discharge data using any indication of influenza (ICD-9-CM code 487 or 488) in the medical record for all residents of Maricopa County served by a Maricopa County facility (Andersen et al. 2007; Schwartz et al. 1996). The number of cases per day was then divided by the number of hospital admissions on that date to compute the percentage of encounters with an influenza code for each study period. As in previous research (Hanigan et al. 2008; Katsouyanni et al. 2001), we created an indicator variable to identify peak influenza days within each November–January study period. For each day, indicator variables identified whether the day was above or below the 90th percentile of the distribution of influenza encounters during the study period.

We obtained air pollution data for the study from EPA's air quality system (AQS) database. These data were sourced from continuous $PM_{2.5}$-monitoring equipment, either a Rupprecht and Patashnick Tapered Element Oscillating Microbalance (TEOM) or a MetOne Beta Attenuation Monitor (BAM), that complied with the EPA's Federal Equivalent Method (FEM); an exception to this occurred in the early study seasons where some of the continuous $PM_{2.5}$ TEOM monitors had not yet been given FEM status, though they were collocated with filter-based federal reference method (FRM) monitors at the site and data were comparable. In cases of collocated monitors, continuous (FEM or pre-FEM) monitoring data were used first (sampling at an hourly resolution), with filter-based FRM-monitoring data (sampling at a 24-h resolution on every third day) being substituted if necessary and available. All air sampling equipment used was approved for taking official air pollution measurements and rigorous maintenance and quality assurance plans for the equipment and data were required and verified (40 CFR pt 58 appx A 2014; MCAQD 2013a; ADEQ 2013).

We obtained meteorological data from the Maricopa County Air Quality Department using sensors located within the study area, preferably collocated at the $PM_{2.5}$-monitoring stations, and aggregated all daily ambient temperature and relative humidity data into daily averages for the study area. We obtained rainfall data from the Maricopa County Flood Control Department from sensors located near the $PM_{2.5}$-monitoring stations and aggregated and converted the data into a dichotomous variable of either presence or absence of any measurable precipitation.

Study population

The study population included Maricopa County citizens residing within the $PM_{2.5}$-monitoring stations' 8-km buffer zone who had a Maricopa County hospital encounter with asthma as one of their diagnoses. ArcGIS 10.1 (ESRI 2012) and a Maricopa Country address locator were used to geocode patients' residential addresses, yielding an overall match rate of 94 %.

Statistical methods

We constructed exposure variables for lag days 0, 1, 2, and 3, indicating exposures on the day of the asthma-related hospital encounter and 1, 2, and 3 days before the asthma-related hospital encounter, respectively. The range of lag days was selected based on evidence of a lag effect in existing literature (Morgan et al. 2010; Bell et al. 2008; Johnston et al. 2007). Because the 8-km buffer zones around the monitors overlapped, we aggregated the daily 24-h $PM_{2.5}$ values. The population density between monitor areas was similar and a large portion of the population was within 8 km of two or more monitors; therefore, daily 24-h $PM_{2.5}$ values from the four monitoring stations were averaged together to form a mean pollution value in the study area for each day. Days that exceeded the $PM_{2.5}$ 24-h primary NAAQS of 35.0 $\mu g/m^3$ were categorized as exposure days and the remaining days were categorized as comparison days. In sensitivity analyses, we also evaluated continuous $PM_{2.5}$ data to gauge the dose-response effect between $PM_{2.5}$ and asthma-related hospital encounters.

To estimate the risk of asthma-related hospital encounters, we used generalized estimating equations (GEE), specified with a log link, Poisson distribution, and an exchangeable working correlation structure (Zeger and Liang 1986). Final models regressed the daily counts of asthma-related hospital encounters on dichotomous indicators for high $PM_{2.5}$ days and weekday vs. weekend, continuous measures of daily average humidity and daily average temperature, dichotomous indicators of rain day and high influenza day, and year. Each year included dates November 1 through January 31, 2008–2009, 2009–2010, 2010–2011, and 2011–2012; in our models, 2008–2009 was the referent year. Given the assumption that changes over time in the size of the source population were small, we did not include an offset in our statistical models. Results were generated separately for type of hospital encounter (ED vs. IP) and by age (child vs. adult) to generate estimates of ED visit and IP stay risk for adults and children for each of the lag periods evaluated. Following our main analyses, we conducted additional analyses to evaluate the impact of including patient gender in our models. Results are presented as relative risks (RRs) with 95 % confidence intervals (CIs). All statistical analyses were conducted using SAS version 9.2 and GEE analyses were conducted using SAS Proc GENMOD (SAS Institute Inc., Cary, NC).

Results

During the study period, a total of 28,856 asthma-related hospital encounters occurred over 368 days. The total number of hospital encounters per day ranged from 40 to 116 with a median of 77; overall, 21,422 (74.3 %) of the hospital encounters were ED visits and 7434 (25.7 %) were IP stays. Children aged 0–19 years at the time of the encounter accounted for 10,615 (36.8 %) of the hospital encounters, and adults 20 years of age and older accounted for the remaining 18,241 (63.2 %). Mean numbers of asthma-related hospital encounters among children and adults on non-exceedance days, exceedance days, and lag days 0–3 are shown in Table 1.

$PM_{2.5}$ daily average concentrations ranged from 2.2 to 72.6 μg/m^3, with a mean daily average of 15.6 μg/m^3. A total of 10 exceedance (exposure) days were identified out of the 368 days in the study period (Table 2). On exceedance days, daily average $PM_{2.5}$ concentrations ranged from 37.3 to 72.6 μg/m^3, with a mean of 53.1 μg/m^3. During the study period, the number of exceedances days increased by one each season from 1 day in 2008–2009 to a total of 4 days in 2011–2012.

Weekends accounted for 106 days (28.8 %) and weekdays for 262 (71.2 %) days. Rain occurred on 40 (10.9 %) of the study period days. Daily average humidity ranged from 14 to 89 %, with a mean daily average of 44 %. Daily average temperature ranged from 3 to 25 °C, with a mean daily average of 14 °C.

Data from the continuous $PM_{2.5}$ sensitivity analysis did not produce any significant associations, thus only the analysis of the NAAQS exceedance days is displayed in our results. Table 3 shows the risks of asthma-related hospital encounters for children and adults for the day of a $PM_{2.5}$ NAAQS exceedance as well as 1, 2, and 3 days later. Among children, exceedance of the $PM_{2.5}$ NAAQS was not associated with ED visits or IP stays. Among adults, the adjusted risk of an ED visit was lower on days on which a $PM_{2.5}$ exceedance occurred than on days on which an exceedance did not occur (RR = 0.82, 95 % CI 0.72, 0.92) and risks increased monotonically with increasing days following the exposure: 1 day (RR 1.02; 95 % CI 0.87, 1.20), 2 days (RR 1.19; 95 % CI 1.06, 1.34), and 3 days (RR 1.20, 95 % CI 1.05, 1.37). Exceedance of the $PM_{2.5}$ NAAQS was not associated with IP stays among adults. These results were not notably changed when the models were adjusted for patient sex (e.g., ED visits among adults—lag day 2: RR 1.19; 95 % CI 1.06, 1.34 and lag day 3: RR 1.20; 95 % CI 1.06, 1.36).

Discussion

Our findings suggest that wintertime $PM_{2.5}$ health-standard exceedance days in Phoenix are associated with increased asthma-related ED visits among adults. The known relationship between elevated $PM_{2.5}$ and adverse respiratory health supports the biologic plausibility of our positive results (Antó 2012; Laumbach and Kipen 2012; Tecer et al. 2008; Morgan et al. 2010; Anderson et al. 2012). If the increased $PM_{2.5}$ exposures from BMFs occurred in the evenings, there was a likely lag period before inflammation triggered an asthma exacerbation, or if individuals attempted self-care for 24 h or more before seeking medical attention for their breathing problems, then the observed protective effect on lag day 0 as well as the increased ED hospital encounters 2 to 3 days after exposure is not unexpected. These findings reveal opportunities to improve awareness of the importance of seeking timely medical attention when self-care fails to improve asthma symptoms and control (CDC Vital Signs 2011).

Our observation of increased risk among adults, but not among children, is consistent with the findings of previous research (Smith et al. 1996; Morgan et al. 2010; Andersen et al. 2008), but nonetheless warrants careful consideration. First, despite the ecologic metric of exposure used in our study, children in the Phoenix area may have had different $PM_{2.5}$ exposures than experienced by adults. The increases in $PM_{2.5}$ on the exceedance days considered here occurred in late evening, nighttime, and early morning hours (data not shown) and are thought to be from BMFs; if children

Table 1 Asthma-related hospital encounters among children and adults during the study period November 1 through January 31, 2008–2012

Study period	No. days	Children, 0–19 years		Adults, 20+ years	
		ED Mean (SD)	IP Mean (SD)	ED Mean (SD)	IP Mean (SD)
All days	368	23.5 (7.1)	5.4 (2.8)	34.7 (8.5)	14.9 (4.9)
Non-exceedance days	358	23.6 (7.2)	5.4 (2.8)	34.8 (8.5)	15.0 (4.8)
Exceedance days					
Lag 0	10	21.5 (5.1)	4.3 (2.4)	30.2 (7.4)	10.2 (3.9)
Lag 1	10	21.5 (6.6)	4.0 (2.2)	37.0 (9.6)	13.4 (3.3)
Lag 2	10	24.3 (6.1)	3.8 (2.0)	43.4 (7.3)	14.2 (3.7)
Lag 3	10	20.4 (5.8)	5.3 (2.3)	43.4 (10.0)	15.8 (3.9)

ED emergency department visit, *IP* in-patient visit, *SD* standard deviation

Table 2 Exceedance dates and values for the 24-h $PM_{2.5}$ NAAQS (standard = 35.0 μg/m^3) used in study.

Season	Exceedance dates	Durango Complex	JLG Supersite	South Phoenix	West Phoenix	Aggregate of daily averages
2008–2009	01/01/2009	*61.3*	*49.5*	*69.3*	*87.4*	*66.9*
2009–2010	12/25/2009	*45.4*	*47.2*	N/A	*84.2*	*59.0*
	01/01/2010	*38.5*	28.9	N/A	*56.9*	*41.4*
2010–2011	12/24/2010	23.0	32.4	*50.3*	*43.5*	*37.3*
	12/25/2010	*64.2*	28.7	*82.7*	*55.4*	*57.7*
	01/01/2011	33.8	*64.3*	*53.0*	*99.2*	*62.6*
2011–2012	12/24/2011	28.1	28.2	*51.9*	*45.2*	*38.3*
	12/25/2011	*49.2*	35.0	*60.9*	*67.4*	*53.1*
	12/31/2011	25.3	27.9	*56.4*	*61.3*	*42.7*
	01/01/2012	*74.4*	*55.9*	*70.8*	*89.2*	*72.6*

All $PM_{2.5}$ values in units of μg/m^3 ; italicized values note exceedance of NAAQS

are not typically outdoors during these peak hours, then their $PM_{2.5}$ exposures may be lower than those of adults. Similarly, if children stayed farther from outdoor fire pits then their exposures may have been lower than those of adults in the vicinity. Indeed, if our aggregation of $PM_{2.5}$ measurements overestimated children's actual exposures for this reason, it may have simultaneously underestimated adults' actual exposures. Despite this potential misclassification of exposure, on the days identified in our study as exceedance days, elevated concentrations of $PM_{2.5}$ in the outdoor environment affected individuals of all ages in the Phoenix area.

The lag time between exposure and the hospital encounter that we observed has been reported previously (Andersen et al. 2007; Bell et al. 2008; Galán et al. 2003; Delfino et al. 2009). In a study of the relationship between $PM_{2.5}$ chemical constituent emissions, hospitalization admissions, and the lag between exposure and hospitalization, Kim et al. (2012) noted that patients presenting with cardiovascular symptoms tended to be admitted to the hospital on the day of the exposure, whereas patients with asthma often presented several days later. Kim et al. (2012) also reported that for patients exposed to elemental or organic carbon constituents of $PM_{2.5}$ (e.g., BMF smoke or other products of combustion), lag periods between exposure and hospitalization were several days shorter than for patients exposed to sulfate or nitrate constituents. Wintertime ambient $PM_{2.5}$ in the Phoenix area is generated largely by combustion yielding primarily carbon species and never dominated by nitrate or sulfate secondary particles (Maricopa County Air Quality Department 2014); however, we were unable to evaluate the extent to which specific components of $PM_{2.5}$ may have affected the hospital encounters observed in our study.

Our study has a number of strengths that add to the robustness of the results. First, our study area was spatially focused around ambient air pollution monitors that provided high-quality $PM_{2.5}$ data. Using 8-km buffers and methods similar to those used in a study of PM_{10} and pediatric asthma by Dimitrova et al. (2012), we were able to carefully select our study population. The

Table 3 Associations between 24-h $PM_{2.5}$ National Ambient Air Quality Standards exceedance days and asthma-related emergency department visits and in-patient hospital stays among children and adults in Maricopa County, AZ

	Lag day 0 RR (95 % CI)[a]	Lag day 1 RR (95 % CI)[a]	Lag day 2 RR (95 % CI)[a]	Lag day 3 RR (95 % CI)[a]
Children, ≤19 years				
Emergency department visits	0.91 (0.76, 1.09)	0.89 (0.73, 1.09)	1.04 (0.89, 1.20)	0.89 (0.74, 1.06)
In-patient hospital stays	0.88 (0.64, 1.21)	0.85 (0.63, 1.15)	0.77 (0.59, 1.00)	1.04 (0.84, 1.29)
Adults, 20+ years				
Emergency department visits	0.82 (0.72, 0.92)	1.02 (0.87, 1.20)	1.19 (1.06, 1.34)	1.20 (1.05, 1.37)
In-patient hospital stays	0.76 (0.57, 1.01)	1.05 (0.88, 1.27)	0.99 (0.87, 1.12)	0.99 (0.89, 1.09)

[a] Adjusted for weekday versus weekend, daily average humidity, daily average temperature, rain day, high influenza day, and year

population within the study area was large, with approximately 720,000 people living within 8 km of the study's air pollution monitors (U.S. Census Bureau 2011) and with approximately 29,000 of those residents having a hospital encounter for asthma during the four seasons of the study period. Our detailed hospital discharge data allowed us to select asthma-related hospital encounters based on primary or secondary diagnoses, while also to control for influenza on a daily basis.

Several limitations should also be considered. Sensitivity analysis of the relationship between continuous $PM_{2.5}$ data and asthma hospital encounters did not provide additional information about the relationship between $PM_{2.5}$ and asthma-related hospital encounters; however, measuring the health effect during NAAQS exceedance days in the holiday season was one of our main goals, and thus, use of the limited exceedance days provided relevant results. Our analyses do not fully take into account any additional effect of holiday days, such as changes in diet, travel, or social activities, since all of the $PM_{2.5}$ exceedance days included in our study occurred on Christmas Eve, Christmas Day, New Year's Eve, or New Year's Day. Also, if the stress or disruption of daily life patterns experienced at these holidays affects the risk of asthma (Kasser and Sheldon 2002; Nagata et al. 1999), then our findings may be confounded with effects from stress. In light of the limited evidence of the effect of holiday-related stress on respiratory health (Johnston et al. 2010; Storr and Lenney 1989), we do not anticipate that our results are notably biased by the effect of stress. Additionally, our analyses do not account for pollen or fungal spore counts owing to the lack of high-quality data on bioaerosols in the Phoenix area, though the impact of these allergens is expected to be minimal during months included in our analysis (Pollenlibrary.com 2013; Walkington 1960). Finally, our statistical models did not take into account serial correlation.

Our study identified exceedances of current NAAQS for $PM_{2.5}$ during each holiday season between October 2008 and January 2012. In our data, these exceedances are associated with plausible elevations in the risk of asthma-related ED visits 2 and 3 days later among adults, but not children. Based on the findings of this study, communication of information on the association between high $PM_{2.5}$ days and the increased risk for asthma-related ED visits, especially for adults, can help to increase awareness and support effective action. These findings reveal opportunities for the prevention of asthma-related hospital encounters. Additionally, policies that focus on the reduction of $PM_{2.5}$ during the holiday season may help to decrease $PM_{2.5}$ concentrations and avert asthma-related healthcare events.

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Compliance with ethical standards

Disclaimer The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the Centers for Disease Control and Prevention.

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