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The effect of sandstorms and air pollution on cause-specific hospital admissions in Taipei, Taiwan

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Abstract:

Objective: Relatively little research exists focusing on the impact of air pollution on hospital admissions in Asia compared to the extensive work conducted in the United States and Europe. The issue is of particular importance due to the frequency, intensity, and health effects of Asian sandstorms. This work investigates the relationship between cause-specific hospital admissions and sandstorms and air pollution in Taipei, Taiwan's capital.

Methods: Time-series analyses of asthma, pneumonia, ischemic heart disease, and cerebrovascular disease hospital admissions were performed for Taipei. An 8-year time period (1995-2002) was considered for various indicators of sandstorms and the pollutants NO₂, CO, ozone, SO₂, PM₁₀, and PM_{2.5}. Pollution effects based on single-day lags of 0, 1, 2, and 3 days were explored, along with the average of the same day and previous three days (L03).

Results: The risk of ischemic heart disease admissions was associated with several sandstorm metrics, including indicators of high PM₁₀ levels in the Taipei area, indicators of high PM₁₀ at a monitor designed to measure background pollution, the PM coarse fraction, and the ratio of PM₁₀ to PM_{2.5}. However, the lag structure of effect was not consistent across sandstorm indicators. Hospital admissions for this disease were 16 to 21% higher on sandstorm days compared to other days. This cause was also associated with transportation-related pollutants, NO₂, CO, and PM_{2.5}. Asthma admissions rose 4.48% (95% confidence interval 0.71, 8.38%) per 28 µg/m³ increase in L03 PM₁₀ levels and 7.60% (95% confidence interval 2.87, 12.54%) per 10 ppb increase in L03 ozone. Cerebrovascular disease admissions were associated with PM₁₀ and CO, both at lag 3 days. SO₂ exhibited no relationship with admissions.

Conclusions: Risk of hospital admissions in Taipei may be increased by air pollution and sandstorms. Additional research is needed to clarify the lag structure and magnitude of such effects.

INTRODUCTION

Associations between ambient air pollution and hospital admission rates are well documented in North America and Europe^{1,2} with fewer studies in Asia. It is vital to further our understanding of air pollution and health relationships in Asia, as a number of factors limit the reliability of results extrapolated from Western studies, including differences in health care systems, baseline health status, exposure patterns, air pollutant mixture, and population characteristics.³ Air pollution in Asia is of particular interest given the growing populations, increased economic activity, rise in vehicular traffic, as well as the increasing intensity and occurrence of dust storms originating in Mongolia and China.

During a severe Asian dust storm, particulate matter can be up to 36 times higher than during non-dust periods, whereas concentrations of gaseous pollutants such as ozone (O₃) and sulfur dioxide (SO₂) may be lower due to elevated wind speeds and lowered light and temperature for O₃ formation.^{4,5} The chemical composition of particles during dust storm events may differ from particulate matter at other time periods and locations, and thereby have dissimilar health impacts. A vast literature links airborne particle exposure to an array of adverse health effects including increased risk of premature mortality, hospital admissions, and respiratory symptoms.⁶ While epidemiological studies on the human health impacts of particles have implicated a variety of size fractions, recent research demonstrates that the observed epidemiological associations between PM_{2.5} (particulate matter with an aerodynamic diameter $\leq$ 2.5 microns) and hospital admissions vary by region and season.¹ Such spatial and temporal differences in the health effects estimates of particles could result from variation in chemical composition.

Studies of sandstorm particles in Taiwan and elsewhere in Asia identified higher concentrations of crustal elements (e.g., Ca, Mg, Al, and Fe) than for non-storm particles.^{4,7} Consistent with those results, measurements from dust storms in central Taiwan exhibited elevated concentrations of coarse particles (PM_{10-2.5}),^{7,8} and a Beijing dust storm was reported to contain higher concentrations of particles > 2 microns than were present in non-dust periods.⁵ To what extent is the health of the residents of Taipei affected by the chemical composition and size distribution of particles from sandstorm events? This question is critically important since particles from Asian sandstorms include a higher proportion of coarse particles compared to typical urban particle mixtures found in the cities of both developing and industrialized nations. In addition to these factors, the extrapolation of concentration-response functions from one study region to another is hindered by differences in the underlying population.³ Therefore, air pollution and health studies in East Asia address significant research questions and can help policy-makers to make timelier and more effective air quality and health management decisions.

This study focuses on Taipei, the capital of Taiwan, whose greater metropolitan area includes a population of about six million, with 2.5 million in the city itself. Growing transportation networks and urbanization have increased vehicular pollution. Motor vehicles account for over 95% of carbon monoxide (CO) emissions and 75% of nitrogen oxide (NO_x) emissions, as well as substantial contributions to hydrocarbons, a precursor to O₃.⁹ The valley topography encourages the accumulation of air pollution.

Under certain weather conditions, sand from dust storms originating in Mongolia and China are carried eastward to Taiwan by cold pressure systems. This long-range transport of air pollution influences air quality, contributing about 30 $\mu\text{g}/\text{m}^3$ to particulate matter with an aerodynamic diameter less than 10 microns (PM₁₀) in Taiwan and up to 87% for some episodes for Taipei.^{10,11} In fact, even minor Asian dust storms can influence Taipei's particulate levels.¹¹

As the intensity and frequency of Chinese sandstorms increase,¹² their effects on the health of Taiwanese people may gradually worsen. A multicriteria analysis of environmental quality in Taipei identified air quality and noise as the environmental issues most important to the public, outranking land-use conflicts, drinking water, solid waste, open space, and water pollution.¹³ Air quality was particularly important to residents of downtown areas.

In order to better understand how air pollution affects health in Taipei, a study of air pollution and cause-specific hospital admissions was conducted for an eight-year period considering six ambient air pollutants and sandstorms, using four indicators of sandstorm events. To the best of our knowledge, this is the first study to examine the effect of air pollution on pneumonia or ischemic heart disease hospital admissions in Taiwan. Previous studies of the impact of air pollution and sandstorms on hospital admissions in Taiwan are summarized in the Discussion Section.

METHODS

Eight years of daily data from January 1, 1995 to December 31, 2002 are used for this study of Taipei. Eighteen air monitoring stations in Taipei City and County were operated during the study period by the Taiwan Environmental Protection Agency (TEPA). The considered pollutants were PM_{2.5}, PM₁₀, nitrogen dioxide (NO₂), SO₂, CO, and O₃. The monitoring station instrumentation included β -gauges for PM₁₀ and PM_{2.5}, ultraviolet (UV) absorption for O₃, UV fluorescence for SO₂, chemiluminescence for NO₂, and non-disperse infrared absorption for CO. Weather data, originally collected by the Central Weather Bureau, included temperature and dew point temperature. Twenty-four hour averages were used for daily values of weather and pollution variables. Only two stations monitored PM_{2.5}.

Daily weather values were based on an average of 16 weather monitors throughout the Taipei basin. For generating daily pollution estimates, five monitors were excluded because they were designed to measure transportation or background concentrations. The remaining 13 monitors were employed to measure air quality. Of these 13 monitors, five were in Taipei City and eight in Taipei County. For PM_{2.5}, data from two monitors were averaged to generate daily averages. For the remaining pollutants, we estimated exposure to air pollution in several ways: (1) exposure over the entire Taipei area, based on the 13 air quality monitors; (2) exposure over Taipei City only, based on five monitors; and (3) exposure based on the subset of monitors for which all pairs of monitors had correlations of ≥ 0.75 for a given pollutant. For each of these exposure metrics, daily values across monitors were averaged to generate an overall daily value, including only monitor values with ≥ 16 hours of measurements for a given day.

Sandstorm exposure was modeled using several approaches. First we applied Boolean indicators for the following: (1) PM₁₀ levels $> 115 \mu\text{g}/\text{m}^3$ based on the Taipei area; and (2) PM₁₀ $> 100 \mu\text{g}/\text{m}^3$ at the Yangmin monitoring station. While the use of an indicator variable for high PM₁₀ levels is an imperfect marker of sandstorms, the measure does provide an indication of the extremely high particulate levels that may arise due to sandstorm events. The Yangmin station, located in Taipei City, is designed to monitor background levels; hence its PM₁₀ measurements are less likely to be affected by local pollution sources. It follows that high particulate levels at this station are more likely to represent sandstorm events. Similar approaches, including the use of high PM₁₀ levels at background monitoring stations as an indicator of sandstorms, have been applied previously.¹⁴⁻¹⁸ Because sandstorm events contain a high number of particles in the coarse fraction, we considered coarse particles (PM_{10-2.5}) and the ratio of PM₁₀/PM_{2.5}.

The health effects outcome was the number of hospital admissions for a given day at National Taiwan University Hospital for two cardiovascular causes (ischemic heart disease and cerebrovascular disease) and two respiratory causes (asthma and pneumonia). Admissions for ischemic heart disease included International Classification of Disease Ninth Edition-Clinical Modification (ICD-9-CM) codes 410, 411, and 414. Cerebrovascular disease included ICD-9-CM codes 430 to 437. Asthma was coded as ICD-9-CM 493 and pneumonia as ICD-9-486. Records were originally collected through the National Health Insurance Program, which insures over 96% of the Taiwanese population.¹⁹

A time-series analysis was performed to investigate the relationship between the day-to-day variation in air pollution in Taipei and cause-specific hospital admissions using the following model:

$$\ln(Y_t) = \alpha + \beta C_{t-l}^i + \theta DOW_t + ns(time, df_{time}) + ns(A_t, df_A)$$

where:

Y_t is expected number of hospital admissions on day t

C_{t-l}^i is the concentration of pollutant i on day t at a lag of l days (e.g., $l = 0$ for same day exposure, $l = 1$ reflects the previous day's air pollution)

DOW_t are indicator variables relating to the day of the week

$ns(time, df_{time})$ is a natural cubic spline of time with df_{time} degrees of freedom ($df_{time} = 7$ per year)

$ns(A_t, df_A)$ is a natural cubic spline of apparent temperature (A) on day t with df_A degrees of freedom ($df_A = 6$)

Day of the week was included as a potential confounder as both health effects and air pollution can follow weekly patterns. Long-term trends and seasonality were addressed with splines of a variable representing time. Adjustment by weather was incorporated through apparent temperature, which reflects overall temperature discomfort, accounting for temperature and humidity.²⁰ In the preceding model C_{t-l}^i represents a single day's exposure at various lags. In addition, a model reflecting multiple days of exposure was applied, using the average of exposure over the same day and the previous three days.

This type of time series modeling has been successfully applied to investigate the effects of air pollutants on hospital admissions among other health outcomes.¹ The initial choice of degrees of freedom for the functions of temporal trend and weather were based on previous research.¹ Sensitivity analyses were performed to ascertain the robustness of results to variation in the degrees of freedom for long-term trends. Initial results used 7 degrees of freedom per year for the natural cubic spline of time. In the sensitivity analysis, 3, 5, 9, and 11 degrees of freedom were applied. Previous research demonstrated that results using this model form are generally robust to various measures of control for weather and season.¹ Due to the different number of monitors for the PM metrics (13 for PM₁₀, 2 for PM_{2.5}), daily values for community-level PM_{2.5} estimates exceeded PM₁₀ levels for a small number of days. Sensitivity analysis was conducted omitting these observations.

RESULTS

Over the study period there were 6,909 hospital admissions for ischemic heart disease, 11,466 for cerebrovascular disease, 10,996 for pneumonia, and 10,231 for asthma. Admissions peaked in November for asthma, January for pneumonia, and March for the other causes, and were lowest in August for asthma and cerebrovascular disease and in October for pneumonia and

ischemic heart disease. The respiratory causes followed a stronger seasonal pattern than cardiovascular causes. A summary of weather, pollution, and health data by season is provided in Table 1. No events occurred for 15.0, 2.8, 5.4, and 6.8% of days for the study period for ischemic heart disease, cerebrovascular disease, asthma, and pneumonia, respectively. No days were missing weather data for the study period. Table 1 also compares air pollution levels to World Health Organization (WHO) air quality guidelines.²¹ Taipei experienced high air pollution levels, exceeding WHO guidelines for PM₁₀, PM_{2.5}, and NO₂ for all years.

PM_{2.5} measurements began in April 12, 1997. From that period through December 31, 2002, PM_{2.5} data were missing for 1.3% of the days. Ozone levels rose over the study period, exhibiting a 31.4% increase from 1995 to 2002. Other pollutants exhibited a downward trend, especially SO₂, which declined 58.2%, likely in response to Taipei air quality measures including lower sulfur content for fuel oil in 1996 and diesel oil in 1998.²² Air quality trends over the study period are displayed in Figure 1.

Concentrations of air pollutants can co-vary due to similar sources, atmospheric conditions, seasonal patterns, and related pathways of formation such as through photochemistry. By definition, PM_{2.5} is included in PM₁₀, so the levels of these pollutants can co-vary depending on the concentration of coarse PM. Many of the pollutant concentrations show similar patterns, with the strongest relationship between NO₂ and CO at a correlation coefficient of 0.87, based on the Taipei area-wide data. Other notable associations between pollutant levels were for PM₁₀ with PM_{2.5} (correlation 0.61), SO₂ (0.63), NO₂ (0.64), and CO (0.62). SO₂ was correlated with NO₂ and CO at 0.63 and 0.68, respectively.

Table 2 shows results from the single-lag (i.e., one day) and cumulative exposure models for the percent increase in cause-specific hospital admissions per a given increase (near IQR) in pollution. For all pollutants other than PM_{2.5}, results are shown for three exposure metrics: (1) exposure over the entire Taipei area; (2) exposure for Taipei City only; and (3) exposure based on the subset of monitors for which all pairs of monitors had correlations of ≥ 0.75 for a given pollutant, as described in the Methods Section. Table 2 also provides the average correlation among pairs of monitors for each pollutant and exposure metric. Note that under all three exposure measurements, correlations among monitor values were highest for PM₁₀ compared to other pollutants, indicating that estimates from this pollutant are less likely to suffer misclassification of exposure due to spatial heterogeneity in pollutant levels. Conversely, SO₂ generally had the lowest correlation among monitor pairs. The different exposure metrics identified similar associations between air pollution and hospital admissions. Estimates for exposures based on the city area generally had smaller confidence intervals (i.e., smaller standard error of the regression coefficient) than did estimates based on the entire Taipei area.

Statistically significant relationships were observed for ischemic heart disease admissions and same day pollution for NO₂ and CO and L03 exposure for PM_{2.5}. Cerebrovascular hospital admissions were associated with PM₁₀, NO₂, and CO at lag 3 days. Asthma admissions were associated with L03 PM₁₀ and O₃ at lags of one or two days or L03. No statistically significant associations were observed for pneumonia and any pollutant. SO₂ did not exhibit any statistically significant relationships with any cause of admissions.

Table 1. Summary of hospital admissions, weather, and pollution in Taipei, 1995 to 2002, and comparison to WHO guidelines

	Yearly	Spring	Mean Summer	Fall	Winter	Minimum	Maximum	Interquartile range (IQR)	
<i>Weather (°C)</i>									
Temperature	23.1	24.5	28.9	16.9	22.0	7.8	33.0	8.78	
Dew point temperature	18.3	19.5	23.6	13.0	17.3	-0.5	26.7	7.7	
<i>Hospital Admissions (admissions / day)</i>									
Ischemic heart disease	2.4	2.2	2.3	2.4	2.5	0	11	2	
Cerebrovascular disease	3.9	3.8	3.7	4.0	4.2	0	12	3	
Asthma	3.0	3.5	2.6	4.2	3.8	0	14	3	
Pneumonia	3.8	2.6	3.5	4.4	4.5	0	21	3	
<i>Air pollutant levels (daily)^a</i>									<i>WHO guideline^b</i>
PM _{2.5} (µg/m ³)	31.6	27.7	29.8	32.4	36.7	0.50	355.0	20.2	10
PM ₁₀ (µg/m ³)	49.1	41.9	44.8	49.1	60.4	12.7	215.5	27.6	20
NO ₂ (ppb)	26.4	23.3	24.2	27.3	30.7	3.2	72.0	9.5	21
SO ₂ (ppb)	4.7	3.5	5.7	3.9	5.4	0.2	26.9	3.6	7.5
O ₃ (ppb)	21.4	22.6	18.0	20.5	24.5	3.7	53.4	10.5	38
CO (ppm)	0.9	0.8	0.9	0.9	1.0	0.3	3.6	0.4	

^a Pollutant levels based on the Taipei area (2 monitors for PM_{2.5}, 13 monitors for all other pollutants).

^b WHO NO₂, SO₂, and O₃ guidelines based on mass per volume were converted to volume mixing ratios assuming standard temperature and pressure. The SO₂ WHO guideline is for a 24-hour average. The WHO guideline for daily 8-hour maximum O₃ was converted to a daily average assuming an 8-hr/24-hr ratio of 1.33. All other guidelines are for annual averages.

Table 2. Percent increase in cause-specific hospital admissions per specific increase in pollutant, using single lag and cumulative lag models, with various exposure metrics

Note: Statistically significant associations are shown in bold. L0 = same day, L1 = previous day, L2 = lag 2 days, L3 = lag 3 days, L03 = average of same day and three preceding days.

	Ischemic heart disease	Cerebrovascular	Asthma	Pneumonia
<i>PM_{2.5} (% change in admissions per 20 µg/m³)</i>				
<i>Exposure based on 2 monitors</i>				
L0	3.48 (-0.39, 7.51)	-2.22 (-50.2, 0.67)	0.46 (-2.41, 3.42)	0.06 (-2.74, 2.94)
L1	3.55 (-0.30, 7.56)	-1.30 (-4.08, 1.55)	-1.36 (-4.33, 1.71)	0.34 (-2.446, 3.20)
L2	3.32 (-0.50, 7.29)	0.24 (-2.49, 3.04)	-0.83 (-3.67, 2.10)	-0.59 (-3.38, 2.29)
L3	2.80 (-1.04, 6.79)	1.21 (-1.41, 3.90)	-0.78 (-3.63, 2.16)	-0.44 (-3.22, 2.41)
L03	8.38 (2.28, 14.84)	-1.45 (-5.58, 2.87)	-1.75 (-6.21, 2.92)	-0.61 (-4.87, 3.85)
<i>PM₁₀ (% change in admissions per 28 µg/m³)</i>				
<i>Taipei area (13 monitors), average (avg) correlation between monitor pairs 0.82</i>				
L0	1.91 (-1.25, 5.17)	-1.41 (-3.80, 1.04)	2.63 (-0.01, 5.35)	0.75 (-1.80, 3.36)
L1	0.39 (-2.73, 3.61)	-1.95 (-4.31, 0.48)	1.79 (-0.82, 4.48)	0.16 (-2.36, 2.74)
L2	1.80 (-1.33, 5.04)	0.77 (-1.62, 3.23)	2.20 (-0.41, 4.88)	0.47 (-2.04, 3.03)
L3	2.01 (-1.14, 5.26)	2.64 (0.21, 5.12)	1.87 (-0.71, 4.50)	-0.70 (-3.19, 1.85)
L03	2.91 (-1.52, 7.55)	0.01 (-3.33, 3.47)	4.48 (0.71, 8.38)	0.31 (-3.22, 3.97)
<i>Taipei City (5 monitors), avg correlation between monitor pairs 0.89</i>				
L0	2.08 (-1.04, 5.30)	-1.27 (-3.64, 1.16)	2.53 (-0.09, 5.21)	0.88 (-1.64, 3.46)
L1	0.43 (-2.64, 3.60)	-2.13 (-4.47, 0.27)	1.60 (-0.98, 4.25)	0.50 (-1.98, 3.05)
L2	2.17 (-0.92, 5.36)	0.85 (-1.52, 3.28)	2.21 (-0.37, 4.86)	0.59 (-1.88, 3.13)
L3	2.16 (-0.94, 5.36)	2.52 (0.13, 4.97)	2.08 (-0.47, 4.69)	-0.72 (-3.18, 1.79)
L03	3.40 (-1.19, 8.20)	-0.07 (-3.53, 3.51)	4.68 (0.78, 8.73)	0.83 (-2.83, 4.62)
<i>Monitors with ≥ 0.75 between monitor correlations (12 monitors), avg correlation between monitor pairs 0.86</i>				
L0	1.82 (-1.29, 5.03)	-1.34 (-3.70, 1.07)	2.56 (-0.04, 5.23)	0.86 (-1.67, 3.41)
L1	0.35 (-2.72, 3.52)	-1.98 (-4.31, 0.40)	1.63 (-0.95, 4.26)	0.12 (-2.35, 2.65)
L2	1.93 (-1.15, 5.10)	0.80 (-1.56, 3.22)	1.97 (-0.59, 4.60)	0.52 (-1.94, 3.05)
L3	1.93 (-1.16, 5.12)	2.61 (0.22, 5.05)	2.78 (-0.75, 4.37)	-0.53 (-2.98, 1.97)
L03	2.86 (-1.63, 7.54)	-0.02 (-3.40, 3.49)	4.27 (0.47, 8.22)	0.65 (-2.93, 4.36)
<i>NO₂ (% change in admissions per 28 ppb)</i>				
<i>Taipei area (13 monitors), average (avg) correlation between monitor pairs 0.73</i>				
L0	4.81 (1.04, 8.71)	0.43 (-2.36, 3.29)	1.46 (-1.68, 4.70)	1.34 (-1.67, 4.45)
L1	2.45 (-1.24, 6.27)	-1.37 (-4.10, 1.43)	0.20 (-2.88, 3.38)	0.32 (-2.63, 3.37)
L2	0.28 (-3.26, 3.95)	1.57 (-1.15, 4.36)	-0.14 (-3.11, 2.92)	-0.07 (-2.94, 2.89)
L3	1.08 (-2.46, 4.75)	2.75 (0.02, 5.55)	-0.01 (-2.95, 3.02)	-0.85 (-3.68, 2.07)
L03	1.30 (-1.09, 9.97)	1.84 (-2.17, 6.02)	1.12 (-3.37, 5.81)	0.34 (-3.97, 4.84)
<i>Taipei City (5 monitors), avg correlation between monitor pairs 0.82</i>				
L0	4.23 (0.79, 7.80)	0.35 (-2.20, 2.96)	0.81 (-2.06, 3.76)	1.28 (-1.49, 4.13)
L1	2.28 (-1.07, 5.74)	-1.38 (-3.86, 1.15)	-0.21 (-2.99, 2.65)	0.59 (-2.10, 3.35)
L2	0.24 (-3.00, 3.60)	1.80 (-0.69, 4.34)	0.34 (-2.38, 3.15)	-0.11 (-2.74, 2.59)
L3	1.09 (-2.17, 4.46)	2.42 (-0.07, 4.98)	0.25 (-2.45, 3.04)	-0.79 (-3.40, 1.89)
L03	4.13 (-0.92, 9.44)	1.83 (-1.92, 5.72)	0.94 (-3.26, 5.32)	0.47 (-3.59, 4.71)
<i>Monitors with ≥ 0.75 between monitor correlations (8 monitors), avg correlation between monitor pairs 0.84</i>				
L0	4.36 (0.82, 8.02)	0.43 (-2.20, 3.13)	0.86 (-2.09, 3.89)	1.47 (-1.37, 4.39)
L1	2.23 (-1.21, 5.80)	-1.54 (-4.09, 1.08)	-0.38 (-3.23, 2.57)	0.50 (-2.26, 3.33)
L2	-0.18 (-3.50, 3.24)	1.76 (-0.79, 4.37)	0.22 (-2.57, 3.09)	-0.08 (-2.76, 2.68)
L3	0.94 (-2.39, 4.38)	2.47 (-0.09, 5.09)	0.23 (-2.53, 3.08)	-0.60 (-3.27, 2.14)

L03	3.94 (-1.31, 9.47)	1.85 (-2.06, 5.92)	0.85 (-3.50, 5.41)	0.70 (-3.52, 5.10)
<i>SO₂</i> (% change in admissions per 5 ppb)				
<i>Taipei area</i> (13 monitors), avg correlation between monitor pairs 0.71				
L0	2.75 (-0.50, 6.12)	0.18 (-2.26, 2.68)	1.05 (-1.67, 3.84)	0.81 (-0.89, 4.57)
L1	-0.18 (-3.37, 3.11)	-2.01 (-4.40, 0.44)	-0.87 (-3.53, 1.85)	0.60 (-2.05, 3.32)
L2	-0.64 (-3.71, 2.53)	0.15 (-2.19, 2.54)	1.00 (-1.57, 3.64)	-0.42, -2.96, 2.17)
L3	2.30 (-0.81, 5.50)	1.35 (-0.98, 3.73)	-0.83 (-3.33, 1.73)	-1.56 (-4.04, 0.99)
L03	1.99 (-2.59, 6.78)	-0.16 (-3.56, 3.35)	0.46 (-3.32, 4.40)	0.08 (-3.67, 3.98)
<i>Taipei City</i> (5 monitors), avg correlation between monitor pairs 0.82				
L0	2.48 (-1.06, 6.15)	-0.38 (-3.03, 2.35)	0.31 (-2.63, 3.34)	1.38 (-1.54, 4.39)
L1	-0.28 (-3.76, 3.32)	-2.76 (-5.35, -0.09)	-1.27 (-4.16, 1.70)	-0.14 (-3.01, 2.82)
L2	-0.34 (-3.73, 3.15)	-0.08 (-2.65, 2.55)	0.88 (-1.95, 3.78)	-0.13 (-2.92, 2.74)
L3	3.37 (-0.07, 6.93)	0.74 (-1.82, 3.37)	-1.14 (-3.89, 1.70)	-1.71 (-4.45, 1.11)
L03	2.78 (-2.52, 8.36)	-1.40 (-5.26, 2.62)	-0.27 (-4.58, 4.24)	-0.42 (-4.70, 4.06)
<i>Monitors with ≥ 0.75 between monitor correlations</i> (6 monitors), avg correlation between monitor pairs 0.81				
L0	3.07 (-0.36, 6.60)	-0.10 (-2.65, 2.52)	0.37 (-2.45, 3.28)	1.43 (-1.38, 4.32)
L1	0.11 (-3.24, 3.57)	-2.50 (-4.99, 0.05)	-1.10 (-3.86, 1.74)	-0.32 (-3.06, 2.51)
L2	-0.36 (-3.60, 2.99)	-0.05 (-2.50, 2.47)	0.79 (-1.90, 3.55)	-0.43 (-3.09, 2.31)
L3	3.14 (-0.15, 6.54)	0.78 (-1.67, 3.29)	-0.88 (-3.51, 1.82)	-1.84 (-4.46, 0.85)
L03	3.16 (-1.92, 8.50)	-1.06 (-4.75, 2.78)	-0.09 (-4.20, 4.19)	-0.77 (-4.85, 3.48)
<i>O₃</i> (% change in admissions per 10 ppb)				
<i>Taipei area</i> (13 monitors), avg correlation between monitor pairs 0.72				
L0	-2.74 (-6.55, 1.23)	-0.45 (-3.46, 2.64)	2.47 (-1.05, 6.12)	0.78 (-2.51, 4.19)
L1	-0.22 (-3.81, 3.50)	-2.32 (-5.03, 0.46)	4.54 (1.28, 7.90)	1.58 (-1.44, 4.70)
L2	3.02 (-0.53, 6.69)	-1.81 (-4.42, 0.87)	5.32 (2.17, 8.56)	-0.36 (-3.23, 2.58)
L3	0.45 (-2.99, 4.01)	-0.96 (-3.58, 1.73)	2.41 (-0.64, 5.56)	1.89 (-1.01, 4.88)
L03	0.61 (-4.44, 5.93)	-2.81 (-6.58, 1.11)	7.60 (2.87, 12.54)	1.91 (-2.34, 6.35)
<i>Taipei City</i> (5 monitors), avg correlation between monitor pairs 0.85				
L0	-2.22 (-5.72, 1.41)	-0.18 (-2.93, 2.66)	2.42 (-0.81, 5.75)	1.38 (-1.64, 4.49)
L1	-0.83 (-4.13, 2.58)	-2.45 (-4.95, 0.12)	3.84 (0.84, 6.94)	1.50 (-1.29, 4.37)
L2	3.19 (-0.15, 6.64)	-1.84 (-4.31, 0.68)	4.57 (1.61, 7.61)	-0.54 (-3.23, 2.23)
L3	0.57 (-2.69, 3.93)	-0.71 (-3.19, 1.84)	1.38 (-1.50, 4.34)	1.94 (-0.81, 4.76)
L03	0.63 (-4.22, 5.73)	-2.76 (-6.39, 1.02)	6.61 (2.08, 11.35)	2.20 (-1.90, 6.47)
<i>Monitors with ≥ 0.75 between monitor correlations</i> (9 monitors), avg correlation between monitor pairs 0.84				
L0	-2.44 (-5.98, 1.24)	-0.15 (-2.94, 2.72)	2.57 (-0.70, 5.94)	0.90 (-2.15, 4.03)
L1	-0.78 (-4.11, 2.66)	-2.29 (-4.81, 0.30)	4.19 (1.16, 7.32)	1.52 (-1.30, 4.41)
L2	3.20 (-0.16, 6.67)	-1.87 (-4.34, 0.66)	4.77 (1.80, 7.82)	-0.48 (-3.18, 2.29)
L3	0.45 (-2.82, 3.82)	-0.77 (-3.26, 1.78)	1.75 (-1.14, 4.71)	-0.48 (-3.18, 2.29)
L03	0.52 (-4.34, 5.63)	-2.68 (-6.31, 1.09)	7.13 (2.59, 11.87)	1.99 (-2.11, 6.26)
<i>CO</i> (% change in admissions per 0.5 ppm)				
<i>Taipei area</i> (13 monitors), avg correlation between monitor pairs 0.75				
L0	7.00 (2.08, 12.15)	0.34 (-3.25, 4.06)	3.29 (-0.74, 7.49)	1.91 (-1.97, 5.95)
L1	2.95 (-1.71, 7.82)	-0.52 (-3.97, 3.05)	-0.49 (-4.25, 3.41)	0.03 (-3.65, 3.85)
L2	0.21 (-4.20, 4.82)	2.58 (-0.80, 6.08)	-0.84 (-4.43, 2.88)	0.36 (-3.20, 4.04)
L3	0.93 (-3.47, 5.53)	3.65 (0.26, 7.15)	-0.48 (-4.02, 3.18)	-1.29 (-4.77, 2.32)
L03	5.08 (-1.62, 12.23)	3.20 (-1.82, 8.47)	0.74 (-4.62, 6.40)	0.21 (-5.03, 5.73)
<i>Taipei City</i> (5 monitors), avg correlation between monitor pairs 0.88				
L0	6.20 (2.09, 10.46)	0.06 (-2.95, 3.17)	1.68 (-1.68, 5.15)	1.24 (-2.02, 4.60)
L1	2.61 (-1.25, 6.62)	-0.56 (-3.43, 2.39)	-1.19 (-4.29, 2.01)	-0.01 (-3.06, 3.13)
L2	0.27 (-3.42, 4.09)	2.00 (-0.81, 4.89)	-0.83 (-3.83, 2.26)	0.57 (-2.40, 3.62)

L3	1.12 (-2.57, 4.96)	2.99 (0.17, 5.89)	-0.35 (-3.32, 2.71)	-0.85 (-3.78, 2.16)
L03	5.09 (-0.72, 11.25)	2.57 (-1.75, 7.07)	-0.31 (-4.90, 4.50)	0.31 (-4.23, 5.06)
<i>Monitors with ≥ 0.75 between monitor correlations (11 monitors), avg correlation between monitor pairs 0.81</i>				
L0	6.51 (1.90, 11.33)	0.18 (-3.19, 3.67)	2.87 (-0.91, 6.79)	0.98 (-1.68, 5.76)
L1	2.58 (-1.74, 7.10)	-0.66 (-3.87, 2.66)	-0.71 (-4.20, 2.91)	-0.12 (-3.54, 3.42)
L2	-0.05 (-4.17, 4.24)	2.39 (-0.77, 5.65)	-0.73 (-4.08, 2.73)	0.37 (-2.95, 3.80)
L3	1.13 (-2.99, 5.44)	3.19 (0.03, 6.45)	-0.41 (-3.72, 3.01)	-1.08 (-4.34, 2.30)
L03	4.87 (-1.53, 11.68)	2.82 (-1.96, 7.83)	0.51 (-4.60, 5.89)	0.30 (-4.71, 5.57)

Sandstorm days were identified for 2.1% of days for the indicator based on PM₁₀ levels > 115 µg/m³ in the Taipei area, and for 1.6% of days for the indicator using PM₁₀ > 100 µg/m³ at the Yangmin background monitoring station. The correlation between these two indicators was 0.64. Table 3 shows the relationship between the various sandstorm indicators and cause-specific hospital admissions. No sandstorm metric demonstrated associations with cerebrovascular, asthma, or pneumonia hospital admissions. However, all sandstorm measures exhibited a relationship with ischemic heart disease admissions. The lag structure of this association was not consistent across various metrics.

Table 3. Percent increase in cause-specific hospital admissions for various sandstorm indicators

Note: Statistically significant associations are shown in bold. L0 = same day, L1 = previous day, L2 = lag 2 days, L3 = lag 3 days, L03 = average of same day and three preceding days.

	Ischemic heart disease	Cerebrovascular	Asthma	Pneumonia
% change in admissions comparing days with PM ₁₀ > 115 µg/m ³ to other days				
L0	3.08 (-10.85, 19.19)	-1.92 (-14.58, 12.62)	-8.82 (-23.88, 9.22)	-2.60 (-15.11, 11.74)
L1	-4.55 (-17.83, 0.89)	-7.39 (-19.56, 6.61)	-2.51 (-18.20, 16.18)	-0.29 (-12.91, 14.16)
L2	16.17 (1.17, 33.39)	2.44 (-10.47, 17.20)	10.33 (-6.55, 30.25)	-4.41 (-16.72, 9.72)
L3	7.09 (-6.89, 23.16)	-1.75 (-14.30, 12.63)	12.86 (-4.27, 33.07)	8.97 (-4.37, 24.18)
% change in admissions comparing days with PM ₁₀ > 100 µg/m ³ at Yangmin background station to other days				
L0	0.41 (-14.75, 18.28)	-1.45 (-15.71, 15.21)	-1.32 (-19.04, 20.28)	-10.74 (-23.91, 4.71)
L1	-10.96 (-25.14, 5.92)	4.07 (-10.60, 21.15)	0.90 (-16.99, 22.65)	2.20 (-12.03, 18.74)
L2	20.81 (3.80, 40.61)	-0.80 (-14.93, 15.67)	12.85 (-6.23, 35.81)	-1.85 (-15.72, 14.31)
L3	12.22 (-3.81, 30.93)	-6.41 (-19.95, 9.41)	25.04 (4.62, 49.45)	12.97 (-2.14, 30.40)
% change in admissions per 13 µg/m ³ increase in coarse PM				
L0	2.68 (0.03, 5.40)	0.24 (-2.13, 2.68)	0.96 (-2.02, 4.04)	-0.99 (-3.32, 1.40)
L1	3.11 (0.51, 5.77)	1.37 (-0.97, 3.77)	-0.33 (-3.28, 2.71)	-1.30 (-3.57, 1.03)
L2	1.60 (-0.98, 4.25)	0.96 (-1.36, 3.33)	0.16 (-2.78, 3.19)	-0.48 (-2.75, 1.85)
L3	1.87 (-0.71, 4.51)	-0.14 (-2.47, 2.25)	0.14 (-2.81, 3.18)	1.09 (-1.18, 3.42)
L03	4.71 (0.88, 8.68)	0.54 (-2.84, 4.04)	0.43 (-3.78, 4.82)	0.03 (-3.26, 3.44)
% change in admissions per 0.75 increase in PM ₁₀ /PM _{2.5}				
L0	0.03 (-0.84, 0.90)	0.13 (-0.66, 0.93)	0.72 (-0.27, 1.72)	-0.28 (-1.10, 0.54)
L1	0.44 (-0.34, 1.24)	-0.49 (-1.43, 0.46)	-0.06 (-1.22, 1.11)	-0.32 (-1.09, 0.47)
L2	0.26 (-0.61, 1.15)	-0.24 (-1.12, 0.64)	-0.25 (-1.48, 1.00)	0.24 (-0.44, 0.92)
L3	1.17 (0.46, 1.89)	-0.68 (-1.66, 0.31)	-0.25 (-1.50, 1.01)	0.27 (-0.40, 0.95)
L03	0.52 (-1.04, 2.10)	-0.26 (-1.94, 1.44)	-0.27 (-2.55, 2.05)	0.01 (-1.40, 1.44)

Several sensitivity analyses were conducted. Analysis of the relationship between air pollution or sandstorms and cause-specific hospital admissions for all lags and outcomes considered was repeated for exposure metrics that rely on community-level PM₁₀ or PM_{2.5} values

(PM₁₀ in the Taipei area, PM₁₀ in Taipei City only, PM₁₀ based on highly correlated monitors, PM_{2.5}, coarse PM, sandstorm indicator of PM₁₀ > 115 µg/m³, and PM₁₀/PM_{2.5}), by omitting the small number of days where community-level PM_{2.5} exceeded PM₁₀ values. Effect estimates were similar to those of the original analysis (correlation 0.998).

The original results used 7 degrees of freedom per year for the natural cubic spline of temporal trend. We also applied 3, 5, 9, and 11 degrees of freedom per year for the Taipei-wide exposure metrics for PM₁₀, NO₂, SO₂, O₃, and CO for all lags and outcomes. Results were robust to more or less aggressive adjustment for long-term trends and seasonality.

DISCUSSION

Our results indicate a link between ambient air pollution and sandstorm and hospital admissions in Taipei. In particular, higher rates of ischemic heart disease admissions were linked with CO, NO₂, and PM_{2.5}, all pollutants related to transportation sources, as well as several indicators of sandstorms, such as coarse particles. Asthma admissions were associated with PM₁₀ and O₃. Cerebrovascular admissions were associated with PM₁₀ and CO, and displayed an implied relationship with NO₂. Results were consistent across multiple exposure metrics for air pollution. However, results for various sandstorm indicators implicated different lag structures, so further research is needed to clarify the lag structure and magnitude of such effects.

A limited number of other studies also examined the effects of sandstorms or air pollution on hospital admissions in Taiwan. Table 4 summarizes these previous studies and includes one study on emergency room visits. Results from this study are provided for comparison. A previous study found higher asthma hospital admissions with PM₁₀, SO₂, NO₂, CO, and O₃, whereas we observed effects for PM₁₀ and O₃ only. Possible explanations for differences in the results are the study designs, timeframe, and city, as different regions may have divergent pollutant mixtures.

No other studies of pneumonia hospital admissions and air pollution in Taiwan were identified in a literature review. This research is also unique because it is the only study to observe statistically significant relationships with total cerebrovascular disease hospital admissions, which were identified for PM₁₀ and CO. Other work found relationships with specific forms of the disease and for emergency room visits for cerebrovascular disease. Two previous works found higher hospital admissions for cardiovascular causes in Taipei and one in Kaohsiung. We observed a relationship between NO₂, CO, and PM_{2.5} with ischemic heart disease, a subset of the cardiovascular outcomes modeled in other studies.

Other work has examined the relationship between air pollution and hospital admissions and related events in China, finding associations between CO, SO₂, NO_x, or PM₁₀ and emergency room visits for colds, pneumonia, and bronchitis³⁰; total suspended particles (TSP) and unscheduled non-surgical outpatient visits³¹; SO₂ and pediatric outpatient and surgery visits³¹; TSP and SO₂ and hospital admissions³²; SO₂ and TSP and non-surgical outpatient visits³³; SO₂ and TSP and hospital outpatient and emergency visits³⁴; and TSP and SO₂ and COPD hospital admissions.³⁵

Table 4. Summary of air pollution or sandstorms and hospital admissions studies in Taiwan

Note: Associations are statistically significant, unless otherwise noted. ICD-9 codes match those used in this study, except where otherwise specified.

Study region (time period)	Study design	Results
Asthma		
<i>This study</i> Taipei (1995 to 2002)	Poisson time-series modeling. Sandstorms modeled through multiple indicators.	Associations with L1, L2, and L03 O ₃ and L03 PM ₁₀ .
Taipei (1996 to 2001) ¹⁴	Dust storm event defined as PM ₁₀ > 125 µg/m ³ at Yangmingshan station. Compared admissions on storm days to those a week before and week after. Considered lags of 0, 1, 2, and 3 days.	Risk of admissions 8% higher two days after storm; results not statistically significant.
Taiwan (1998-2001) ²³	Auto-regressive integrated moving average time-series approach.	Seasonal trends in admissions associated with monthly mean PM ₁₀ , SO ₂ , CO, and NO ₂
Kaohsiung (1996 to 2003) ²⁴	Case-crossover design. Compared air pollution on date of admission with pollutant levels one week before and after. Used cumulative lag of same day and up to two days previous.	PM ₁₀ , SO ₂ , NO ₂ , CO, and O ₃ associated with admissions on cool days (< 25 °C). All but SO ₂ also associated on warm days (≥ 25 °C). Largest association for NO ₂ on cool days.
Taipei (1 year) ²⁵	Cross-sectional study based on monthly hospital admissions for respiratory illness	NO ₂ and PM ₁₀ levels significantly correlated with admissions. No consistent association with O ₃ or SO ₂ .
Pneumonia		
<i>This study</i> Taipei (1995 to 2002)	Poisson time-series modeling. Sandstorms modeled through multiple indicators.	No statistically significant associations.
Cerebrovascular		
<i>This study</i> Taipei (1995 to 2002)	Poisson time-series modeling. Sandstorms modeled through multiple indicators.	Associations with PM ₁₀ and CO at three day lags.
Kaohsiung (1997 to 2000) ²⁶	Outcome was stroke (ICD-9 430 to 438). Case-crossover approach. Compared air pollution on date of admissions to days a week before and week after. Considered lags up to 2 days.	PM ₁₀ , NO ₂ , SO ₂ , CO, CO, and O ₃ associated with intracerebral hemorrhage (ICD-9 431 and 432) and ischemic stroke admissions (ICD-9 433 and 435) on warm days (≥ 20 °C). CO associated with ischemic stroke admissions on cool days (< 20 °C).

Taipei (1996 to 2001) ¹⁷	Outcome was stroke (ICD-9 430 to 438). Dust storm event defined as $PM_{10} > 125 \mu g/m^3$ at Yangmingshan station. Compared admissions on storm days to those a week before and week after. Considered lags of 0, 1, 2, and 3 days.	Non-statistically significant results for risk of stroke admissions for dust storms compared to control days at a three-day lag. Significant associations for primary intracerebral hemorrhagic stroke (ICD-9 431 and 432).
Taipei (Apr. 12, 1997 to Dec. 31, 2002) ²⁷	Outcome was emergency admissions for those > 50 years (ICD-9 430-437). Poisson time-series model.	Effects for O_3 at lag 0, CO at lag 2, $PM_{2.5}$ at lag 3, and PM_{10} at lag 3 days.
Cardiovascular		
<i>This study</i> Taipei (1995 to 2002)	Outcome was ischemic heart disease (ICD-9 410, 411, and 414). Poisson time-series modeling. Sandstorms modeled through multiple indicators.	Associations with same day NO_2 and CO, and with L03 $PM_{2.5}$. Also associated with presence of sandstorms as indicated by high PM_{10} levels overall and at a background station (L3), coarse PM (L0, L1, and L03), and the ratio of PM_{10} to $PM_{2.5}$ (L3).
Kaohsiung (1997 to 2000) ²⁸	Outcome was cardiovascular disease (ICD-9 410-429). Case-crossover approach. Compared air pollution on date of admissions to days a week before and week after. Considered lags up to 2 days.	PM_{10} , NO_2 , CO, and O_3 associated with admissions on warm days ($\geq 25^\circ C$). All but O_3 also associated on cool days ($< 25^\circ C$).
Taipei (1997 to 2001) ²⁹	Outcome was cardiovascular disease (ICD-9 410-429). Case-crossover approach. Compared day of admissions to days one week before and 1 week after. Considered cumulative lag up to two days previous.	PM_{10} , NO_2 , CO, and O_3 associated with admissions on warm days ($\geq 20^\circ C$). PM_{10} , NO_2 , and O_3 associated on cool days ($< 20^\circ C$)
Taipei (1996 to 2001) ¹⁶	Outcome was cardiovascular disease (ICD-9 410-429). Dust storm event based on PM_{10} levels at Yangmingshan station. Compared admissions on storm days to those a week before and week after. Considered lags of up to 3 days.	Risk of admissions increased 3.65% on days following a storm; results not statistically significant.

Previous research has investigated the impacts of sandstorms and coarse particles. Several studies based on Taipei found indication that risk of adverse health events is higher after Asian dust storm events, however results were not statistically significant.^{14,16,17} Such results include analysis of clinical visits for allergic rhinitis from 1997 to 2001¹⁸ and respiratory and circulatory disease mortality from 1995 to 2000.¹⁵ In Korea, dust events were linked with respiratory symptoms of persons with bronchial asthma,³⁶ and weakly associated with mortality.³⁷ Statistically significant relationships were not observed between PM_{10-2.5} and mortality in China³⁸ or dust events and hospital admissions in British Columbia.³⁹ Studies that have examined PM_{2.5} and coarse PM together indicate an adverse effect of coarse PM on health, but stronger effects for PM_{2.5}.⁴⁰ Previous research also supports the theory that coarse PM contributes to cardiovascular hospital admissions.⁴⁰

Our study uses one of the longest study periods applied to research of air pollution and hospital admissions in Taipei. It is also one of the first to investigate the impacts of air pollution on ischemic heart disease and pneumonia hospital admissions in Taiwan. Limitations of our methodology include the use of ambient monitors as a surrogate for actual exposure. This method, while commonly employed, does not include differences in daily activity patterns, sub-community heterogeneity in concentrations, which may differ by pollutant, or occupational exposure. Advantages of this approach are the use of existing measurements and the ability to thereby study a larger population over an extended period of time. Misclassification of exposure may differ by pollutant, as indicated by the variation in correlations of pollutants between monitors. The limited number of monitors measuring PM_{2.5} hinders our ability to investigate this pollutant and related measures such as coarse PM. While we used a variety of metrics to gauge sandstorm levels, these definitions are imperfect and may not fully capture the presence of sandstorm events. Further, the sandstorm indicators applied in this research are related to high PM₁₀ levels, including at a background monitoring station, and coarse particles, but do not assure that the particulate pollution is in fact the result of sandstorm events. Future research on sandstorms and health could include air quality modeling such as trajectory analysis or source apportionment techniques to confirm that particles on days identified as sandstorm days originate from sandstorm sources.

The outcome variable was the number of hospital admissions rather than the hospital admissions rate; therefore changes in populations over time could potentially affect our results. However, an investigation that covered about 72% of our study period found no significant trends in population rates for Taipei residents older than 50 years.²⁷ Because the concentrations of air pollutants can co-vary due to similar sources and atmospheric conditions, it is not possible to distinguish among the effects of highly correlated pollutants, such as NO₂ and CO. A single pollutant may act as a surrogate for another pollutant or a pollutant mixture from the same source or formation pathway. Therefore, results may be indicative of the pollutant mixture or a related pollutant, rather than the individual pollutant modeled.

Results from this study provide evidence that air pollution in Taipei may increase risk of hospital admissions for a variety of causes and that sandstorm events in particular may adversely impact health. Additional research is needed to better understand physiological mechanisms, to further identify the relative toxicity of various pollutants in Taiwan, and to measure the extent to which the health consequences of dust storm particles and other pollutants in this area differ from the health impacts of air pollution in other regions of the world. Such efforts would better enable decision-makers to effectively design air pollution control strategies. The use of multi-city air pollution studies for Taiwan, such as have been conducted in Europe and North America,

would minimize sample size concerns and potentially lower uncertainty surrounding effect estimates.

Main message box:

- The presence of sandstorms and coarse particles may be associated with elevated risk of hospital admissions.
- Exposure to ambient air pollution may be associated with increased risk of respiratory and cardiovascular hospital admissions in Taiwan's capital and other regions with similar air pollution characteristics.

Policy implications:

- Air pollution and sandstorms appear to present a substantial risk to public health in Asia, which is essential information for the development of air pollution control strategies and warning systems for sandstorms.
- Given the growing transportation systems and the high levels of air pollution currently experienced in this and other parts of Asia, in-country evidence on related health impacts is critically important to decision-makers.

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Figure Caption

Figure 1. Percent change in pollutant levels in Taipei, 1995 to 2002

Note: The baseline year is 1995 for all pollutants except PM_{2.5}, for which the baseline year is 1997. PM_{2.5} data are not available for 1995 to 1996. The PM_{2.5} 1997 data reflects April 12 to December 31, 1997.

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