Emergency Visits for Thunderstorm-Related Respiratory Illnesses Among Older Adults

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Abstract

Background: The typical climatological changes seen with thunderstorms are expected to increase in severity with rising global temperatures. Acute respiratory illnesses have been hypothesized to result from atmospheric changes that occur during thunderstorms. However, large-scale evidence on this phenomenon has been limited.

Methods: U.S. climatologic data were combined with geographic data on emergency medical utilization among Medicare beneficiaries to analyze the relationship between thunderstorm events and acute respiratory illness. Daily thunderstorms, temperature, wind speed, and pollution levels in 3,127 U.S. counties during 1999-2012 were linked to Medicare claims data on emergency visits for respiratory illness. Event study analyses assessed for changes in emergency visits in the 20 days preceding and following thunderstorm events.

Results: Overall, 22.1 million emergency respiratory visits and 1,897,909 thunderstorms were analyzed. Thunderstorms were associated with rises in temperature and particulate matter prior to the storm followed by declines in both variables on the day of storm and days after. Emergency visits peaked the day prior to thunderstorm by an additional 1.2 visits per million Medicare beneficiaries overall (95%CI 1.0-1.5) and an additional 3.8 visits per million beneficiaries with asthma or COPD (95%CI 2.8-4.8), corresponding to relative increases of 0.8% and 0.7%. In the ±3 days surrounding thunderstorms, there were 2.9 additional visits per million beneficiaries overall (95%CI 1.6-4.1) and 12.2 additional visits per million beneficiaries with asthma or COPD (95%CI 8.6-15.9).

Conclusion: Thunderstorms were associated with increases in emergency visits for respiratory illness among Medicare beneficiaries, particularly those with asthma or COPD.

INTRODUCTION

The typical climatological changes seen with thunderstorms, including precipitation, high winds, and drops in temperature, are expected to increase in severity with rising global temperatures.[1] Acute respiratory illnesses, particularly acute asthma exacerbations, have been hypothesized to result from atmospheric changes that occur during thunderstorms, sometimes termed "thunderstorm asthma." Thunderstorm asthma refers to outbreaks of acute asthma exacerbations temporally associated with a thunderstorm, a phenomenon that was first reported in the literature after 106 patients presented with an acute asthma exacerbation within a 48-hour period following a thunderstorm in Birmingham, England in 1983.[2] More recently in 2016, hospitals, doctors' offices, and emergency services in Victoria, Australia were overwhelmed by an epidemic of acute asthma exacerbations following a large thunderstorm, resulting in 8 asthma deaths and thousands of patients presenting to hospitals for asthma treatment.[3-5]

Asthma affects an estimated 7.7% of American adults and acute episodes can be triggered by several factors, including inhaled allergens, air pollution, infections, or changes in weather.[6-8] Similar symptoms with associated small airway obstruction are seen in acute exacerbations of chronic obstructive pulmonary disease (COPD) which can also have allergic, infectious, and weather-related triggers.[9-11] Thus, atmospheric changes associated with thunderstorms, such as rapid changes in temperature, particulate matter, wind (including "outflow" winds which can occur during precipitation), and pollen count could, in theory, lead to acute respiratory illness.

In its most recent report, the Intergovernmental Panel on Climate Change predicts that as global temperatures rise, there will be an increase in intensity of weather events, including thunderstorms, which may adversely impact health, including respiratory disease.[12,13] Despite the need to better understand how atmospheric changes that occur during thunderstorms may relate to acute respiratory illness, empirical analyses of this relationship have been limited in geographic scope, size, frequency of thunderstorm events analyzed, and assessment of specific environmental changes that occur during thunderstorms.[4,14-22]

Using data on emergency visits for respiratory illness among Medicare beneficiaries during 1999-2012, linked to daily county-level data on lightning strikes, precipitation, temperature, wind speed, pollution, and pollen levels, we analyzed the relationship between thunderstorm events and acute respiratory illness. We focused on atmospheric changes that could plausibly trigger exacerbations of asthma or COPD, hypothesizing that emergency department visits for respiratory illness would be increased around thunderstorm activity.

METHODS
Data Sources

Thunderstorm events were identified using the U.S. National Lightning Detection Network (NLDN) database maintained by the U.S. National Oceanic and Atmospheric Administration (NOAA). NLDN monitors lightning activity across the U.S. in real-time through a network of lightning sensors that use magnetic direction and time-of-arrival measurements to accurately identify each lightning event. In the contiguous United States, NLDN is estimated to capture more than 95% of cloud-to-ground lightning flashes (only cloud-to-ground lightning flashes were included in this study; cloud-to-cloud lightning was not included).[23] Our analysis used aggregate lightning data published by NOAA that provided counts of all lightning strikes within a specific county and day from January 1999 to December 2012.

In the primary analysis, thunderstorms were identified at the county-day level based on the presence of any cloud-to-ground lightning flashes and positive precipitation. In additional analyses, alternative definitions of thunderstorms were used to capture storms of varying severity, including county-day observations with any lightning flashes (with or without precipitation), as well as county-day observations with lightning, precipitation, and above-median wind speed on the lightning day. The dataset contained approximately 16 million county-day observations (3,127 counties each observed on approximately 5,110 days).

Temperature and precipitation data were obtained from NOAA's Global Historical Climatology Network (GHCN) station monitoring data. Wind speed was obtained from NOAA's Global Summary of the Day (GSOD) station monitoring data and North American Regional Reanalysis (NARR) data. Data on air pollution, including concentrations for fine particulate matter ($PM_{2.5}$), coarse particulate matter (PM_{10}), ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and carbon monoxide (CO), were obtained from the U.S. Environmental Protection Agency's Air Quality System (AQS) station monitoring data. Daily total pollen count data were obtained from the American Academy of Allergy Asthma & Immunology (AAAAI) and were available for 61 monitoring sites in 59 counties.

County-day level averages were computed for precipitation, wind speed, temperature, and air quality using station-monitoring data. Because monitoring station networks are often sparse, not all counties have weather or pollutant monitoring stations within their geographic boundaries. To maximize sample coverage, we created county-level weather and pollution measures using an inverse distance weighting approach.[24] Specifically, for each county, we identified monitoring stations that were within 20 miles of the county's geographic centroid and then computed mean weather and pollution measures across these stations, weighting each station's observations by the inverse of the station's distance to the county's centroid. Health care utilization and demographic data on Medicare beneficiaries aged ≥ 65 years were obtained from the Medicare Provider Analysis and Review (MedPAR) file, the Outpatient Standard Analytic Files, and the Master Beneficiary Summary File (MBSF, including the Chronic Conditions

segment). Data files covered Medicare claims and enrollment information for 100% of beneficiaries during the study period, 1999-2012. MedPAR was used to identify all emergency room visits for respiratory illness that resulted in hospitalization and the outpatient file to identify visits that did not result in hospitalization. History of asthma or COPD was obtained from the Chronic Conditions segment of the MBSF. For each calendar day, we identified all living fee-for-service (FFS) beneficiaries whose first diagnosis of either asthma or COPD occurred on or before that day. To ensure accurate measures of chronic conditions, analyses were restricted to beneficiaries continuously enrolled in fee-for-service Medicare for 2 years.

Outcome measures

Our primary outcome was the county-level rate of daily emergency department (ED) visits with a primary diagnosis of any respiratory illness as defined by *International Classification of Diseases, 9th Revision* (ICD-9) codes 460-519. A broad definition for respiratory illness was used since specific categories such as asthma, COPD, or reactive airways disease may be unrecognized, undocumented, or not coded as the primary diagnoses by the treating physician. The fraction of Medicare beneficiaries in a county who had an ED claim for respiratory illness was computed for each day, both overall and for beneficiaries with a history of asthma or COPD.

Statistical Analysis

The relationship between thunderstorm events, climatological and air pollutant changes, and respiratory illness was estimated using an event-study approach that focused on changes in environmental and health outcomes in the days before versus after a given thunderstorm event. This analysis was premised on the assumption that the specific timing of thunderstorm events, conditional on covariates such as seasonal indicator variables, was uncorrelated with non-thunderstorm-mediated factors that may also affect respiratory illness, a quasi-experimental approach. The following county-day-level statistical model was estimated for each of several dependent environmental variables (precipitation, wind speed, temperature, fine particulate matter, and pollen) as well rates of ED visits for respiratory illness:

$$Y_{ct} = \alpha + \sum_{j=-19}^{20} \beta_j Thunderstorm_{c(t+j)} + Covariates_{ct} \qquad (1)$$

where Y_{ct} was the outcome for county c on day t; $Thunderstorm_{c(t+j)}$ was a series of binary indicators for whether a thunderstorm occurred in county c on the jth day since day t; $Covariates_{ct}$ denote fixed effect indicators for county (approximately 3,100 indicators), year (14 indicators), month-of-year (12 indicators), and day-of-week (7 indicators). Results of this regression were first presented by plotting the estimated values for $\beta_{20}, \beta_{19}, \ldots, \beta_1, \beta_0, \beta_{-1}, \ldots, \beta_{-18}, \beta_{-19}$ and their associated 95% confidence intervals, tracing out the evolution of environmental and health outcomes 20 days before and 20 days after a thunderstorm event occurred. To facilitate interpretation overall and between sub-groups, the coefficients were also summed in

the ±3 days surrounding thunderstorms to depict with a single point estimate the relationship between thunderstorm events and emergency visits for respiratory illness. Robust variance estimators were used in all analyses to account for clustering of outcomes and thunderstorm events within counties.

The relationship between emergency respiratory visits and thunderstorm events was estimated for Medicare beneficiaries overall and separately for beneficiaries with a prior history of asthma or COPD. In addition, in sub-group analyses with formal tests for interactions, thunderstorms were stratified by severity into three categories (any lightning, lightning with precipitation, and lightning with precipitation and high winds), an analysis conducted to assess whether increases in emergency respiratory visits were greater for more severe storms. Finally, because thunderstorms could in theory lead to increases in medical care for reasons not specifically related to respiratory health, a falsification analysis was conducted using ED visits for three conditions unlikely to be affected by thunderstorms: sepsis (ICD-9: 995.91), pulmonary embolism (ICD-9: 415.1), and deep vein thrombosis (ICD-9: 453.4).[25]

Analysis were performed in Stata (v. 14). The 95% confidence interval around reported estimates reflects 0.025 in each tail or P≤0.05. The study was approved by the institutional review board at the National Bureau of Economic Research.

RESULTS

Overall, 46,581,214 Medicare beneficiaries enrolled in fee-for-service Medicare for at least two years from 1999-2012 were analyzed, including 9,792,731 (21%) beneficiaries with an ED visit for respiratory illness (**Table 1, Panel A**). Among 16,057,960 county-day level observations, thunderstorms (lightning strikes accompanied by precipitation) occurred in 1,897,909 county-days (12%), corresponding to a mean rate of 43 days per year per county. Compared with days without thunderstorms, days with thunderstorms were associated with more precipitation, higher wind speed, and warmer air temperature (**Table 1, Panel B**). There was substantial regional variation in thunderstorm frequency, with thunderstorms most likely in the northern and eastern Gulf Coast, as well as in the Mountain West areas (**Figure 1**).

Changes in atmospheric conditions around thunderstorm events

Thunderstorms were associated with significant changes to local atmospheric conditions (**Figure 2**). Precipitation increased on storm days, increasing by an average of 7.5 millimeters, representing a 260% increase out of a daily mean of 2.9 millimeters. Changes in wind speed occurred in the days surrounding thunderstorms, with decreasing wind speed observed before storms, rapid increases on thunderstorm days, and decreasing wind speed with return to baseline in the days following. A rise and subsequent fall in temperature, particulate matter, and other pollutants was observed in the days surrounding thunderstorms (**Figure 2** and **Supplement Figure 1**). No statistically significant changes in pollen counts were observed prior to thunderstorms in the 59 counties where data were available (**Supplement Figure 1**).

Emergency visits for respiratory illness

Emergency visits for respiratory illness increased in the several days prior to thunderstorm events, peaked on the day prior, and returned to the baseline rate on the day following the event (**Figure 3**). Among Medicare beneficiaries overall, visits peaked on the day prior to thunderstorms, increasing by 1.2 per million beneficiaries (95% CI 1.0 to 1.5) on the day prior to the thunderstorm, or a 0.8% increase above the daily mean of 153.4 visits per million beneficiaries (**Figure 3, Panel A**). Among patients with a history of COPD or asthma, the absolute increase in emergency visits for respiratory illness associated with thunderstorms was larger (**Figure 3, Panel B**). Emergency respiratory visits rose by 3.8 per million beneficiaries on the day prior to thunderstorms (95% CI 2.8 to 4.8; P < 0.001), corresponding to a 0.7% increase above the daily mean of 559.1 visits per million beneficiaries with asthma or COPD. An increase in emergency visits for respiratory illness in the day prior to thunderstorms was also observed for Medicare beneficiaries without a prior history of asthma or COPD, although the absolute increases were smaller in magnitude compared to those with asthma or COPD (**Figure 3, Panel C**).

To facilitate interpretation, regression coefficients from the above event studies were summed in the ±3 days surrounding thunderstorms to depict with a single point estimate the relationship between thunderstorm events and emergency respiratory visits (**Table 2**). Among beneficiaries overall and among beneficiaries with asthma or COPD, thunderstorms were associated with an additional 2.9 and 12.2 emergency respiratory visits per million beneficiaries, respectively, in the ±3 days surrounding thunderstorms, corresponding to 1.9% and 2.2% increases above mean daily emergency visit rates.

In sub-group analyses that stratified thunderstorms by severity, more severe thunderstorms (i.e., those associated with precipitation alone or precipitation and high winds compared to lightning alone) were associated with larger increases in emergency respiratory visits for beneficiaries overall and those with asthma or COPD (**Table 2**). For example, storms with any lightning flashes (i.e., with or without precipitation and/or high winds) were not associated with substantial increases in emergency respiratory visits in the ±3 days surrounding thunderstorms. In contrast, among beneficiaries with asthma or COPD, thunderstorms with precipitation and high wind speeds were associated an additional 19.7 emergency respiratory visits per million beneficiaries compared to an additional 12.2 visits for storms with precipitation alone (p=0.08 for difference).

Sensitivity analyses

Thunderstorms were not associated with changes in emergency visits for sepsis, pulmonary embolism, or deep vein thrombosis, three falsification conditions chosen to assess whether the relationship between thunderstorms and emergency respiratory visits could be mediated by unobserved factors leading to greater emergency medical care overall (**Supplement Figure 2**).

DISCUSSION

Emergency visits for acute respiratory illness significantly increased in the days before and on days of thunderstorms among Medicare beneficiaries, particularly those with a history of asthma or COPD. This pattern was more pronounced for more severe thunderstorms (those with high winds). Emergency visits peaked on the day before thunderstorms, coinciding temporally with rapid increases in particulate matter concentration and temperature, before returning to normal levels in the following days. No relationship was observed between thunderstorms and emergency hospitalizations for control conditions like sepsis or pulmonary embolism for which biologically plausible relationships with the environmental changes that occur during thunderstorms have not been proposed.

This is the first large-scale study to combine high-frequency climatologic data in the U.S. with detailed geographic data on emergency medical care for acute respiratory illnesses to evaluate the relationship between thunderstorms and emergency visits for respiratory illness. Our findings suggest that climatological changes that typically precede and accompany a thunderstorm, including rising particulate matter concentration and temperature, may predispose to acute respiratory disease. The single-day effects observed were modest, with approximately 1 additional emergency respiratory visit per million Medicare beneficiaries on the day before a thunderstorm, and approximately 4 additional emergency visits per million beneficiaries with a history of asthma or COPD on the day preceding the storm. When high winds were part of a thunderstorm, visits increased by an additional 1.8 and 5.7 visits per million beneficiaries, respectively. In the 3-day period surrounding the high-wind thunderstorms, there were 5.3 additional emergency respiratory visits per million beneficiaries overall and 19.7 more per million beneficiaries with COPD or asthma.

While asthma and COPD are common conditions in the American population, large epidemic outbreaks of reactive airway diseases following thunderstorms have not been reported in the U.S. as they have in other parts of the world. Limited research into thunderstorm asthma epidemics, described mostly in Europe and Australia, has led to several hypotheses to explain the phenomenon.[26] In wet conditions such as after precipitation, pollen spores that are normally too large to reach the small airways can rupture from osmotic shock after getting wet, releasing smaller allergenic particles that are small enough to reach the lower respiratory tree and induce allergic bronchoconstriction.[27,28] Winds that accompany thunderstorms, including "outflow" winds (downward drafts of colder air during the storm), can sweep across the land and further distribute these small pollen particles which can subsequently be inhaled by predisposed allergic patients, triggering an exacerbation of reactive airway disease.[17,29,30] Though epidemics suggestive of this proposed mechanism have not been described in the U.S., one study over an 11 year period found a 3% increase in emergency visits for asthma on the days following, but not preceding, thunderstorms in the Atlanta, Georgia area.[19]

Our study found that emergency respiratory visits peaked on the day prior to a thunderstorm, suggesting that the release and spread of small pollen particles by the mechanism described above may not be the primary mechanism of thunderstorm-related respiratory disease in the Medicare population. This is further supported by our findings that in the 59 counties where pollen data was available, no evidence was found of an increase in pollen count around thunderstorms. Emergency respiratory visits most closely mirrored the pattern of rising temperature, particulate matter, and other pollutants on the days before the storm, raising the possibility that antecedent atmospheric changes may be the primary drivers of thunderstorm-related respiratory illness in the older Medicare population. This is consistent with prior studies showing increased acute respiratory illness in the Medicare population associated with increases in both atmospheric particulate matter and temperature.[31,32] The pollen-particle-release mechanism could, however, explain a portion of increased emergency visits seen on the day of the thunderstorm.

Our study has several limitations. First, the study population included patients aged 65 years or older, a population in which asthma is less prevalent compared to both younger adults and children.[6,33] Asthma incidence is highest among children and adolescents, particularly in the southern states[34] where thunderstorms were most concentrated in our study. Additionally, older patients with reactive airway disease are less sensitive to airway hyperreactivity compared to younger patients[35,36] and thus may be less likely to present for emergency care. For these reasons, the amount of additional acute respiratory illness related to thunderstorms may be higher among children and younger adults in whom asthma is more prevalent, more severe, and perhaps more sensitive to atmospheric changes compared to Medicare benificiaries.[20] Second, pollen count data were available for only a small subset of counties, limiting insight into possible pollen-associated epidemics or the ability to focus on patients with allergic asthma specifically, who previous studies have suggested may be most susceptible to acute respiratory illness related to thunderstorms and climatological changes.[27] Third, the use of claims data limits inference into the underlying pathophysiology of those presenting for acute care, making it difficult to draw specific conclusions about the underlying biologic mechanisms of acute respiratory illness related to thunderstorms. Future large-scale study of this phenomenon including children and adults, pollen counts, and more detailed clinical data would be valuable.

In conclusion, thunderstorms were associated with significant increases in emergency visits for respiratory illness among Medicare beneficiaries, particularly those with asthma or COPD. Increases in visits peaked prior to thunderstorm onset and were temporally associated with increases in temperature, particulate matter concentration, and pollutants.

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Table 1. Study population and atmospheric conditions

A. Study population	
Number of beneficiaries	46,581,214
Beneficiaries with respiratory ER visits, %	21.0
Age, y, mean (sd)	77.0 (7.4)
Female, %	58.6
Median household yearly income in ZIP Code area - dollars	54,917
Preexisting medical conditions, %	
Asthma	10.5
Chronic obstructive pulmonary disease	26.5
Alzheimer's disease	16.9
Atrial fibrillation	16.1
Chronic kidney disease	18.7
Diabetes	31.9
Congestive heart failure	30.5
Hyperlipidemia	66.0
Hypertension	77.8
Stroke or transient ischemic attack	16.5

| B. Atmospheric conditions	Days without thunderstorm	Days with thunderstorm
Number of county-days	14,160,051	1,897,909
Precipitation - mm	1.7	10.2
Wind speed - m/s	3.4	3.6
Air temperature - degrees F	53.5	68.9
PM2.5 - ug/m^3	11.5	10.7
PM10 - ug/m^3	23.3	20.1
O_3 – ppb	30.2	29.6
CO – ppm	0.5	0.4
NO_2 – ppm	11.6	8.3
SO_2 – ppm	3.3	2.4
Pollen counts - grains/m^3	169.8	138.0

Notes: Thunderstorms were defined at the county-day level based on any cloud-to-ground lightning flashes and positive precipitation. Panel A shows characteristics of the study population. Household income is expressed in 2019 US dollars. Information on preexisting medical conditions was obtained from the Chronic Conditions Data Warehouse of the Centers for Medicare and Medicaid Services. Panel B shows county-day level atmospheric conditions by thunderstorm status. PM2.5 = particulate matter less than 2.5 microns in diameter. PM10 = particulate matter with a diameter between 2.5 and 10 microns. Ppb = parts per billion. Ppm = parts per million.

Figure 1. Average annual number of thunderstorm days, United States 1999 to 2012
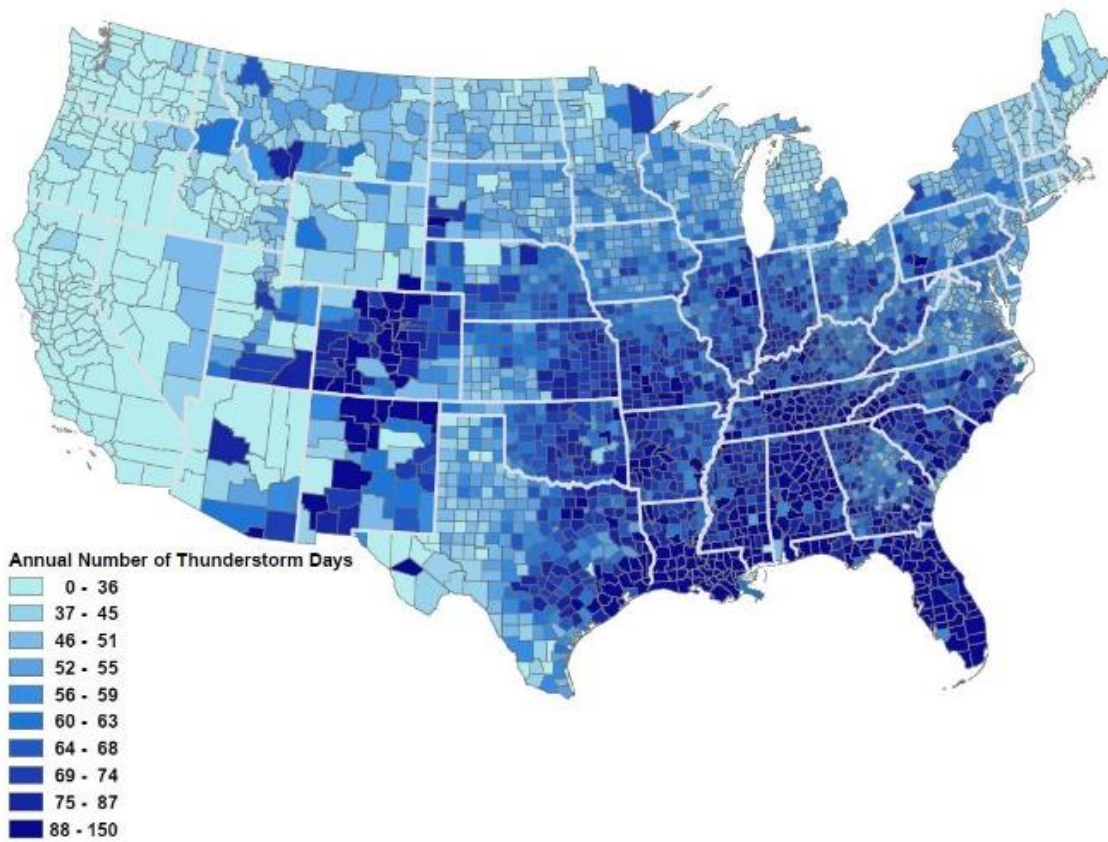

Notes: Map shows annual average number of thunderstorm days during 1999 to 2012, in which thunderstorms were defined as county-days with positive cloud-to-ground lightning flashes and positive precipitation. Counties in the contiguous U.S. were divided into deciles according to thunderstorm frequency. Legend reports the range of frequency by each decile.

Figure 2. Changes in atmospheric conditions around thunderstorms
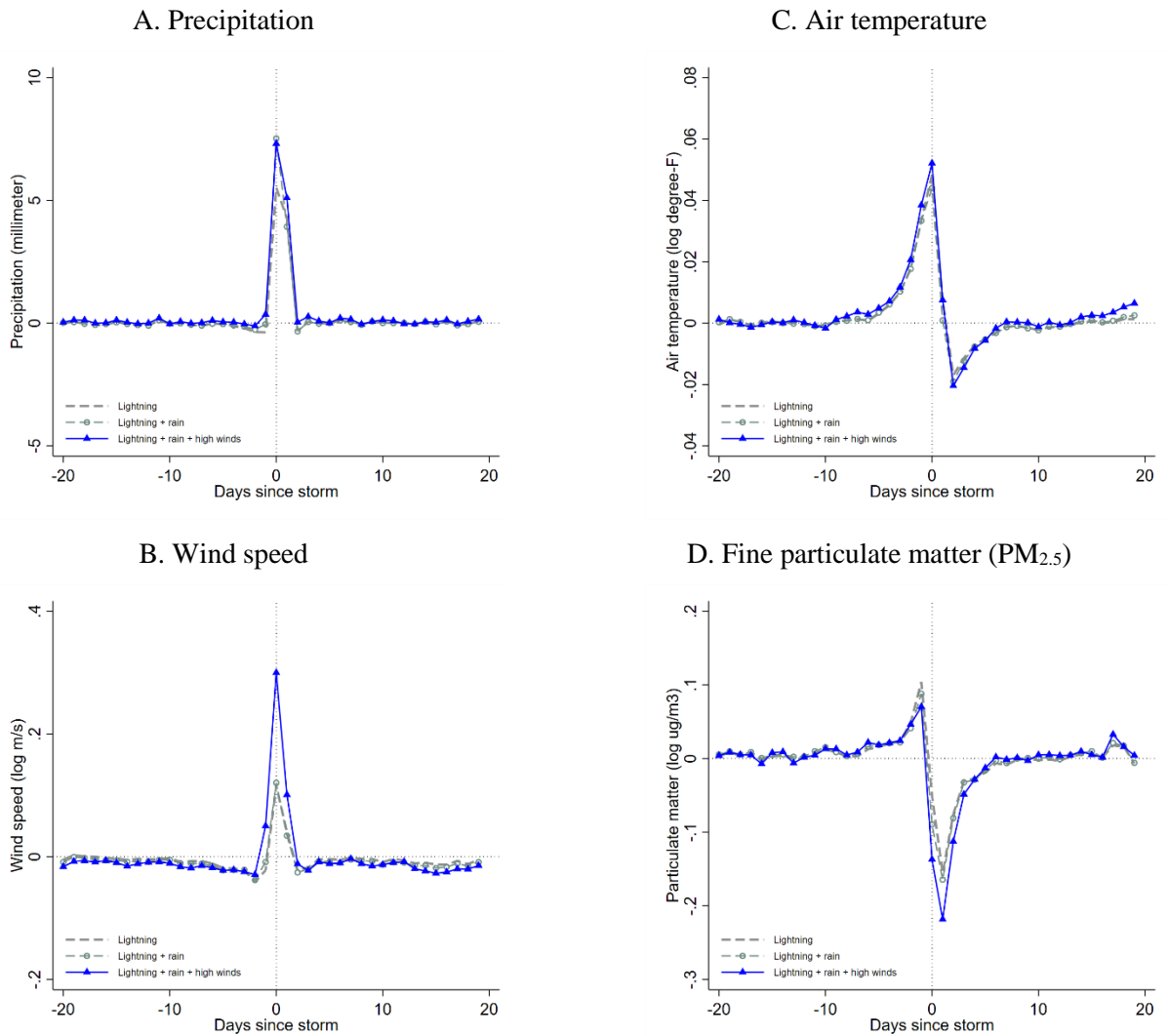
A. Precipitation

C. Air temperature

B. Wind speed

D. Fine particulate matter (PM$_{2.5}$)

Notes: Each panel shows coefficients from a county-day level multivariable linear regression in which the dependent variable was a specific weather outcome and independent variables included 20 lead day indicators, thunderstorm day indicator, and 20 lag day indicators, an event study approach. Lines represent different storm definitions (any lightning; lightning with positive precipitation; and lightning with positive precipitation and above-median wind speed on the storm date). All regressions adjusted for county, year, month-of-year, and day-of-week fixed effects.

Figure 3. Emergency room visits for respiratory illness around thunderstorms
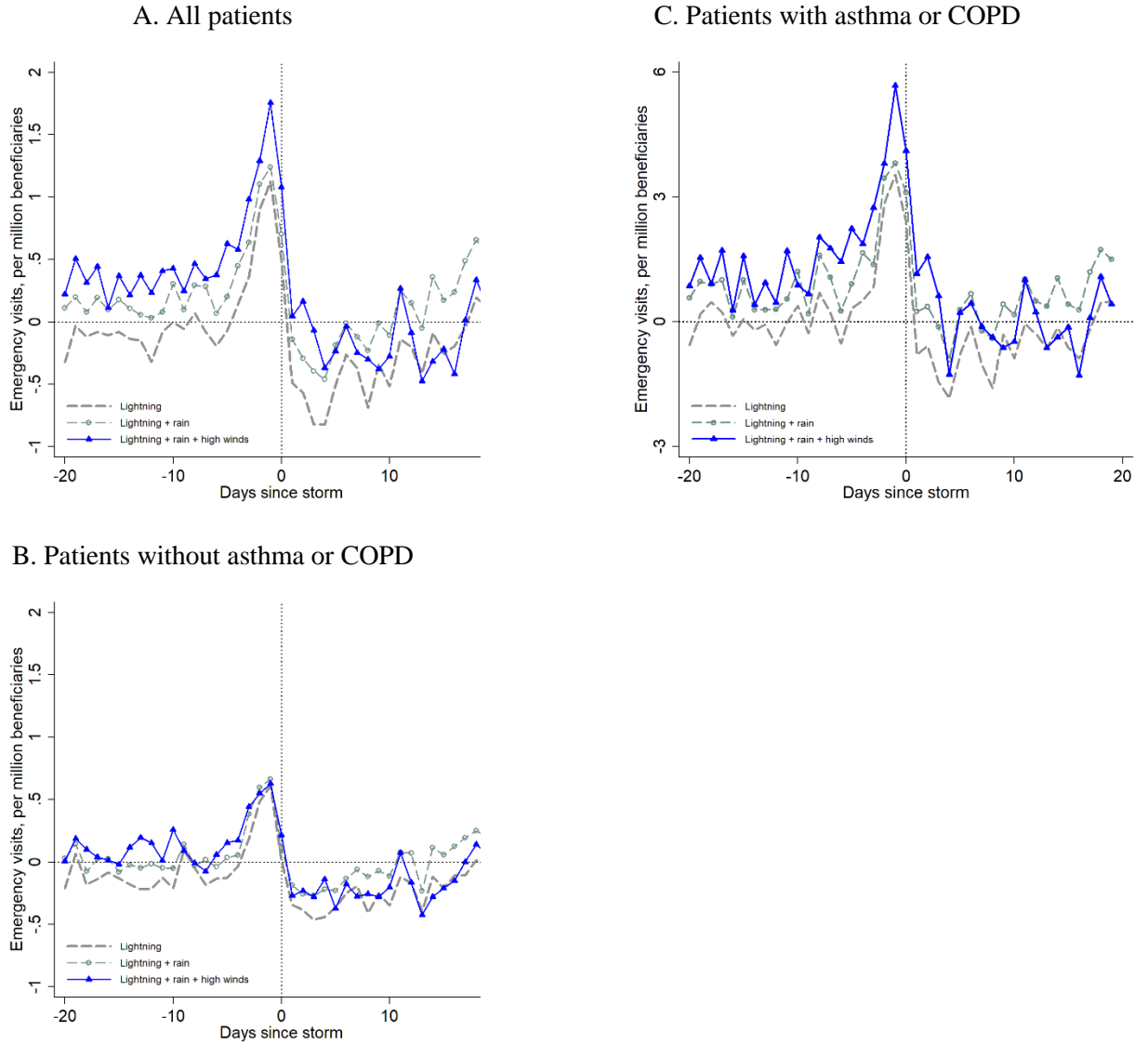
A. All patients

C. Patients with asthma or COPD

B. Patients without asthma or COPD

Notes: Each panel shows coefficients from a county-day level multivariable linear regression in which the dependent variable was the rate of emergency room visits for respiratory illness among Medicare beneficiaries (per million) and independent variables included 20 lead day indicators, thunderstorm day indicator, and 20 lag day indicators, an event study approach. Regressions were estimated separately for three groups of beneficiaries: beneficiaries overall, those with COPD or asthma, and those without COPD or asthma. Lines represent different storm definitions (any lightning; lightning with positive precipitation; and lightning with positive precipitation and above-median wind speed on the storm date). All regressions adjusted for county, year, month-of-year, and day-of-week fixed effects.

Table 2. Changes in emergency room visits for respiratory illness around thunderstorm dates

	Any lightning	Thunderstorm (Lightning plus precipitation)	Thunderstorm with high winds
A. All patients (Mean daily emergency visit rate = 153.4 per million beneficiaries)			
Storm day	0.5 (0.2 to 0.8)	0.7 (0.4 to 1.0)	1.1 (0.7 to 1.5)
	[p=0.001]	[p<0.001]	[p<0.001]
Storm ± 3 days	1.0 (-0.2 to 2.1)	2.9 (1.6 to 4.1)	5.3 (3.8 to 6.8)
	[p=0.09]	[p<0.001]	[p<0.001]
B. Patients without asthma or COPD (Mean daily emergency visit rate = 71.2 per million beneficiaries)			
Storm day	0.02 (-0.2 to 0.2)	0.1 (-0.1 to 0.3)	0.2 (-0.04 to 0.5)
	[p=0.86]	[p=0.29]	[p=0.10]
Storm ± 3 days	0.1 (-0.6 to 0.8)	1.0 (0.3 to 1.8)	1.1 (0.2 to 1.9)
	[p=0.76]	[p=0.006]	[p=0.02]
C. Patients with asthma or COPD (Mean daily emergency visit rate = 559.1 per million beneficiaries)			
Storm day	2.4 (1.4 to 3.4)	3.1 (2.0 to 4.2)	4.1 (2.7 to 5.5)
	[p<0.001]	[p<0.001]	[p<0.001]
Storm ± 3 days	6.8 (3.5 to 10.1)	12.2 (8.6 to 15.9)	19.7 (15.1 to 24.3)
	[p<0.001]	[p<0.001]	[p<0.001]

Notes: Table reports changes in emergency room visits for respiratory illness in the ± 3 days around thunderstorms based on a multivariable regression described in the Methods. "Any lighting" refers to lightning strikes with or without measured precipitation. "Thunderstorm" refers to lightning strikes accompanied by precipitation. "Thunderstorm with high winds" refers to thunderstorms with above-median wind speed on the storm day. 95% confidence interval (in parentheses) and associated *P* values (in brackets) were computed using standard errors adjusted for clustering by county.