

## **Emergency Visits for Thunderstorm-Related Respiratory Illnesses Among Older Adults**

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## **Key Points**

**Question:** With storm severity expected to increase with rising global temperatures, what is the additional burden of acute respiratory illness from atmospheric changes associated with thunderstorms in vulnerable older adults?

**Findings:** In a national study using weather data from 1999-2012, storms were associated with a rise and subsequent fall in temperature and particulate matter counts. In storms with lightning, precipitation, and high winds, emergency visits for acute respiratory illness significantly increased by 5.3 visits per million Medicare beneficiaries overall, 22.6 for those with asthma, 22.4 for those with COPD, and 33.8 for those with asthma and COPD over the  $\pm 3$  days surrounding the storm.

**Meaning:** Older adults, particularly those with asthma and COPD, are at higher risk of acute respiratory hospitalization in the days surrounding thunderstorms, a period characterized by rises in particulate matter and rapid temperature changes.

Thunderstorm-related atmospheric changes are expected to increase in severity with rising global temperatures.<sup>1</sup> Though large-scale evidence is limited, vulnerable populations, such as older adults or those with common chronic respiratory diseases like asthma or chronic obstructive pulmonary disease (COPD), are expected to be susceptible to negative health effects from these changes.<sup>2</sup> The objective of this study was to determine whether increases in emergency department (ED) visits for acute respiratory illnesses occur among Medicare beneficiaries in the days surrounding thunderstorms across the continental United States.

**METHODS:** We used publicly available atmospheric and lightning data from the US National Oceanic and Atmospheric Administration covering all 3,127 counties in the continental US from 1999-2012. We combined this with insurance claims and comorbidity data from Medicare fee-for-service beneficiaries over 65 to identify all ED visits with acute respiratory diagnoses. The relationship between thunderstorm events, climatological and air pollutant changes, and respiratory ED visits 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. Full details of the data sources, research methods, and statistical model design can be found in the **Online Supplement**. Analysis were performed in Stata (v. 14). The 95% confidence interval around reported estimates reflects 0.025 in each tail or  $P \leq 0.05$ . The study was approved by the institutional review board at the National Bureau of Economic Research.

**RESULTS:** Among 46,581,214 Medicare beneficiaries, the mean age was 77.0 years (SD = 7.4); 58.6% were female; chronic diagnosis of asthma was present in 10.5%, COPD in 26.5%, and both

asthma and COPD in 6.6%. We identified 22,118,934 respiratory ED visits and 822,095 county-days with major thunderstorms, defined by lightning, precipitation, and above-median wind speed.

Thunderstorms were associated with rises in temperature and particulate matter prior to the storm, followed by declining levels on the day of and the days following the storm (**Figure 1**). Pollen counts and levels of nitrogen dioxide, ozone, sulfur dioxide, and carbon monoxide were unchanged until dropping after the storm. Above-baseline ED visits peaked the day prior to major storms, with an average 1.8 additional visits per million beneficiaries overall (95% CI 1.4-2.1), 6.3 for those with asthma (95% CI 4.1-8.6), 6.4 for those with COPD (95% CI 5.0-7.8) and 9.4 for those with both asthma and COPD (95% CI 6.2-12.7), corresponding to relative increases of 1.2%, 1.1%, 1.2%, and 1.2%, respectively (**Figure 2**). In the  $\pm 3$  days surrounding these storms, there were 5.3 (95% CI 3.8-6.8) additional visits per million beneficiaries overall, 22.6 (95% CI 16.0-29.2) for patients with asthma, 22.4 (95% CI 17.4-27.4) for those with COPD, and 33.8 (95% CI 24.0-43.6) for those with both. In a falsification analysis to assess for unmeasured confounders that could increase the likelihood of patients presenting to the ED prior to a major thunderstorm, we found no relationship between thunderstorms and ED visits for control conditions like sepsis or pulmonary embolism.

Assuming an average over-65 population of 37.7 million Americans (based on census data), approximately 52,000 additional respiratory ED visits were estimated to occur in the  $\pm 3$  days surrounding major storms during the 14-year study period.

**DISCUSSION:** Emergency visits for acute respiratory illness significantly increased in the days before major thunderstorms among Medicare beneficiaries, particularly those with asthma and/or COPD. Visits were temporally associated with rises in temperature and particulate matter

concentrations, atmospheric changes which have previously been associated with acute respiratory illness in the Medicare population.<sup>3,4</sup>

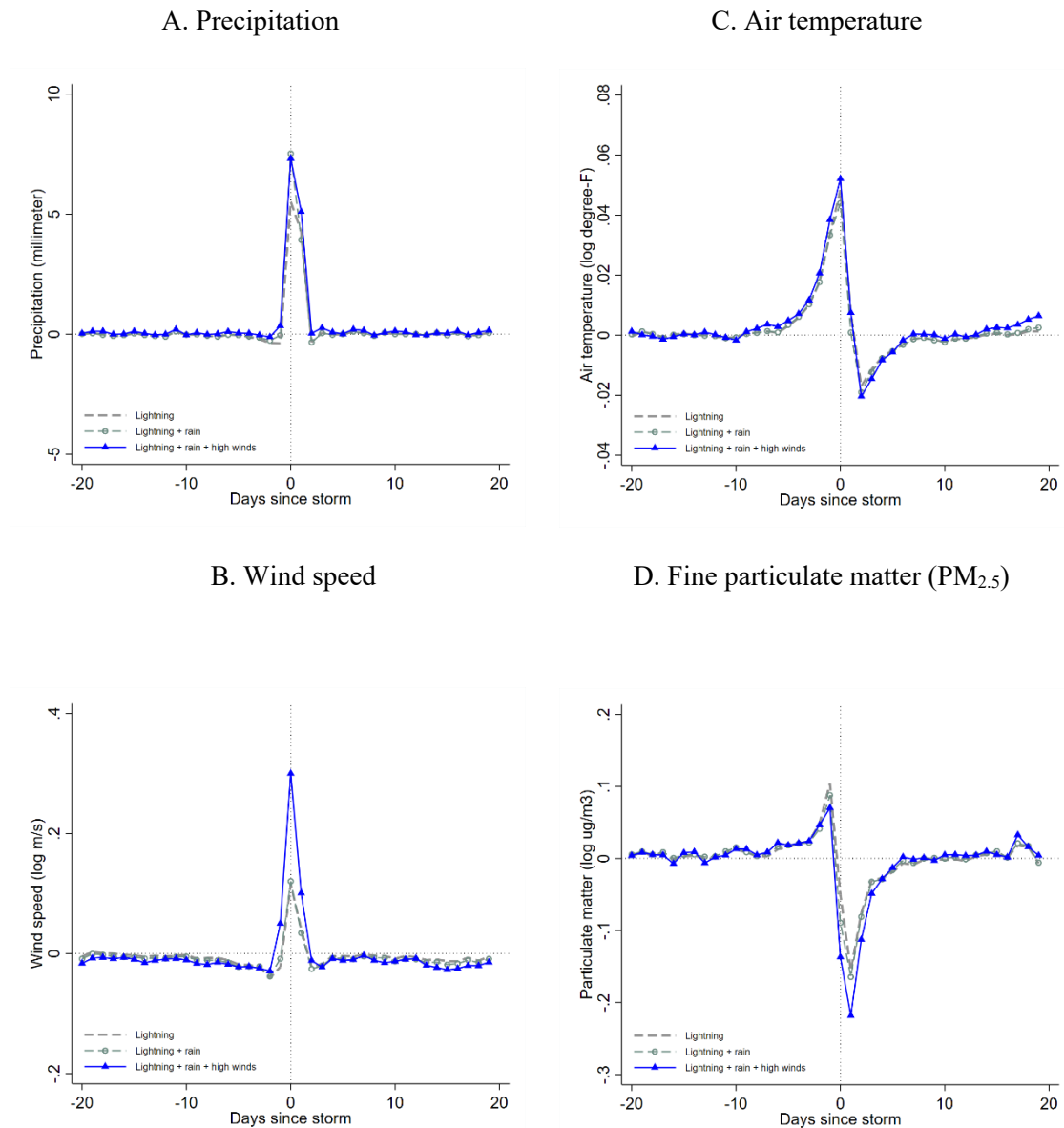
Rare epidemics of asthma following thunderstorms in other countries have been hypothesized to result from pollen grains rupturing when wet, allowing winds to carry small pollen particles that can trigger allergic asthma in susceptible patients.<sup>5</sup> In this study, ED visits peaked prior to the thunderstorm, suggesting pollen particle release from precipitation was not the dominant mechanism. One key limitation of this study is that it may not be generalizable to younger populations where allergic asthma is more common.<sup>6</sup>

This is the first large-scale study to evaluate the relationship between thunderstorms and emergency visits for respiratory illness. Our findings suggest antecedent rises in particulate matter concentration and temperature may be the dominant mechanism of thunderstorm-associated acute respiratory disease in older Americans, which may contribute to strain on the health care system as storm activity increases with rising global temperatures

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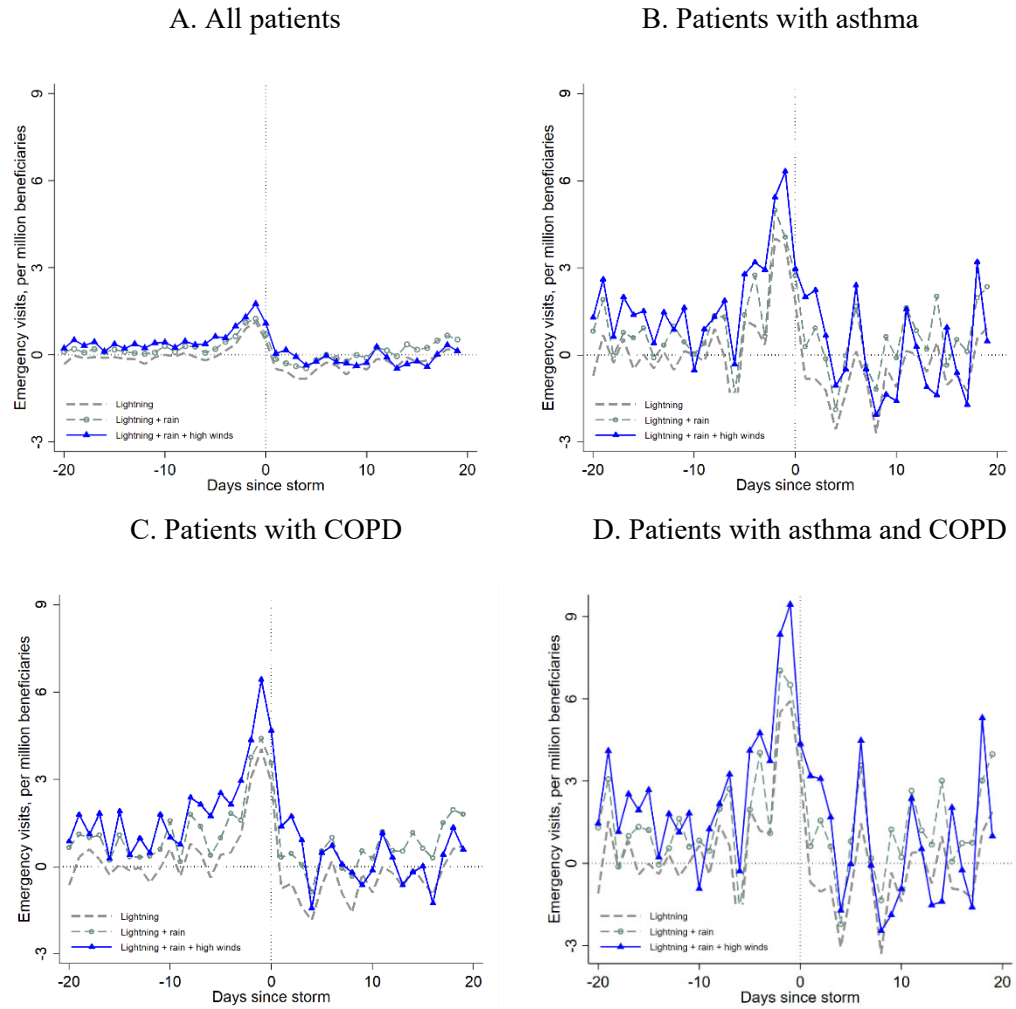
Dr. Zou had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

**Figure 1: Changes in atmospheric conditions around thunderstorms**



**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. Full details are provided in the **Online Supplement**.

**Figure 2: Emergency room visits for respiratory illness around thunderstorms**



**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 four groups of beneficiaries with different chronic conditions history. 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. Full details are provided in the **Online Supplement**.



## REFERENCES:

1. Trapp RJ, Diffenbaugh NS, Brooks HE, Baldwin ME, Robinson ED, Pal JS. Changes in severe thunderstorm environment frequency during the 21st century caused by anthropogenically enhanced global radiative forcing. *Proceedings of the National Academy of Sciences* 2007;104:19719-23.
2. Rice MB, Thurston GD, Balmes JR, Pinkerton KE. Climate Change. A Global Threat to Cardiopulmonary Health. *American Journal of Respiratory and Critical Care Medicine* 2014;189:512-9.
3. Dominici F, Peng RD, Bell ML, et al. Fine Particulate Air Pollution and Hospital Admission for Cardiovascular and Respiratory Diseases. *JAMA* 2006;295:1127-34.
4. Anderson BG, Dominici F, Wang Y, McCormack MC, Bell ML, Peng RD. Heat-related Emergency Hospitalizations for Respiratory Diseases in the Medicare Population. *American journal of respiratory and critical care medicine* 2013;187:1098-103.
5. D'Amato G, Vitale C, D'Amato M, et al. Thunderstorm-related asthma: what happens and why. *Clinical & Experimental Allergy* 2016;46:390-6.
6. CDC. Vital signs: asthma prevalence, disease characteristics, and self-management education: United States, 2001--2009. *MMWR Morbidity and mortality weekly report* 2011;60:547-52.

## Online Supplement

### Emergency Visits for Thunderstorm-Related Respiratory Illnesses Among Older Adults

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## **SUPPLEMENTAL STUDY METHODS**

### **Weather 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).<sup>1</sup> 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<sub>2.5</sub>), coarse particulate matter (PM<sub>10</sub>), ozone (O<sub>3</sub>), nitrogen dioxide (NO<sub>2</sub>), sulfur dioxide

(SO<sub>2</sub>), 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.<sup>2</sup> 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.

### **Clinical Data Sources**

Health care utilization and demographic data on Medicare beneficiaries aged  $\geq 65$  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 by any Medicare beneficiary with a primary diagnosis of any respiratory illness as defined by *International Classification of Diseases, 9<sup>th</sup> 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. In the event-study analysis, we calculate the differences in outcome compared to the storm day for each day in the selected period before or after a storm. We then aggregate the data across all storms in our sample allowing study and visualization of average changes in the days surrounding storms. 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:

$$Y_{ct} = \alpha + \sum_{j=-19}^{20} \beta_j \text{Thunderstorm}_{c(t+j)} + \text{Covariates}_{ct} \quad (1)$$

where  $Y_{ct}$  was the outcome for county  $c$  on day  $t$ ;  $\text{Thunderstorm}_{c(t+j)}$  was a series of binary indicators for whether a thunderstorm occurred in county  $c$  on the  $j^{\text{th}}$  day since day  $t$ ;  $\text{Covariates}_{ct}$  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  $\beta_{20}, \beta_{19}, \dots, \beta_1, \beta_0, \beta_{-1}, \dots, \beta_{-18}, \beta_{-19}$  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  $\pm 3$  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).<sup>3</sup>

Analysis were performed in Stata (v. 14). The 95% confidence interval around reported estimates reflects 0.025 in each tail or  $P \leq 0.05$ . The study was approved by the institutional review board at the National Bureau of Economic Research, a non-profit collaborative research organization, which provided Medicare data through the year 2012 for analysis.

## REFERENCES:

1. North American Lightning Detection Network, Cloud-to-Ground Detection Efficiency. Vaisala Corporation. (Accessed 10/30/2019, at <https://www.vaisala.com/sites/default/files/documents/WEA-ERG-G-NLDN%20DE-Lightning%20Map.pdf>.)
2. Currie J, Neidell M. Air Pollution and Infant Health: What Can We Learn from California's Recent Experience?\*. *The Quarterly Journal of Economics* 2005;120:1003-30.
3. Prasad V, Jena AB. Prespecified falsification end points: can they validate true observational associations? *Jama* 2013;309:241-2.