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Key Points:

- Heavy precipitation events may be related to increased risk of asthma emergency department (ED) visits
- Precipitation thresholds at which excess risk of asthma ED visits occur differ by season
- Satellite data provides a mean of addressing gaps in exposure classification

Supporting Information:

Supporting Information may be found in the online version of this article.

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Assessing the Effect of Precipitation on Asthma Emergency Department Visits in New York State From 2005 to 2014: A Case-Crossover Study

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Abstract The Earth's precipitation patterns are changing, and regional precipitation is expected to continue to increase in New York State (NYS). Heavy precipitation may negatively affect asthma prevalence through its effect on seasonally varying allergens. We employed a threshold analysis using a time-stratified semi-symmetric bi-directional case-crossover study design to assess the effect of increase in precipitation on asthma (ICD-9 code 493.xx, $N = 970{,}903$) emergency department (ED) visits between 2005 and 2014 during non-winter months in NYS. Spatially contiguous gridded meteorological data from North American Land Data Assimilation System (NLDAS) were utilized. We used conditional logistic regression models and stratified the analyses by seasons. During non-winter months, we found a small, statistically significant risk of asthma ED visits for precipitation levels above 50 mm, with differences by season. These results suggest that heavy precipitation may be related to an increased risk of asthma ED visits. Gridded meteorological estimates provide a means of addressing the gaps in exposure classification, and these findings provide opportunities for further research on interactions with aeroallergens and meteorological conditions in the context of climate and health.

Plain Language Summary Heavy precipitation such as rainfall may be associated with increased risk of asthma through its effect on seasonally varying allergens. Using a case-crossover study design, we assessed the effect of precipitation on asthma emergency department (ED) visits between 2005 and 2014 during non-winter months in New York State. A small, statistically significant increased risk of asthma ED visits was observed during non-winter months for precipitation levels above 50 mm, with differences by seasons. The use of gridded meteorological estimates provides a means of addressing gaps in exposure classification. Further research is needed to explore the interactions with allergens and meteorological conditions in the context of climate and health.

1. Introduction

Asthma is a chronic lung disease and a major public health problem affecting approximately 25.1 million individuals in the United States (CDC, 2019). In New York State (NYS), an estimated 1,578,011 adults (10.1% prevalence) and 207,867 children (6.2% prevalence) reported having current asthma in 2018 (CDC, 2018). From 2017–2019, there were over 137,771 emergency department (ED) visits per year for asthma in the state (New York State Department of Health, 2021), and self-reported lifetime asthma prevalence of 14.7% in adults and 13.1% in children in NYS continues to be higher than the national prevalence of 14.5% and 11.3% respectively (CDC, 2021). Asthma causes the inflammation of the airways in lungs, making the air passages particularly sensitive when exposed to asthma triggers and irritants (ALA, 2020). Being a complex multifactorial disease, the manifestations and exacerbations of asthma can be linked to a variety of environmental, social, and genetic factors (Pala et al., 2019). Extensive literature has shown that exposure to air pollutants like ozone and particulate matter (Orellano et al., 2017), and indoor and outdoor allergens such as dust mite, cigarette smoke, pollen and mold, trigger asthma symptoms and may lead to increased morbidity (Stern et al., 2020). Meteorological factors can also contribute to asthma exacerbation (Bodaghkhani et al., 2019; D'Amato et al., 2015). Although several studies have assessed the relationship between increasing heat, or thunderstorms and asthma, fewer studies have sought to understand the association between precipitation and asthma. This analysis aims to fill that gap and explore the association between precipitation and risk of asthma ED visits in NYS.

The latest Intergovernmental Panel on Climate Change (IPCC) report implies that extreme precipitation events are becoming more common in eastern North America and that high precipitation is projected to increase across a majority of North America (IPCC, 2021). Climate trends precipitation indicators have shown that between 1948 and 2008, annual total precipitation has increased by 30.19 mm per decade and precipitation on very wet days has increased by 17.97 mm per decade in NYS (Insaf et al., 2013), and climate projections for NYS suggest that by 2080, regional precipitation will increase by 4%–15% (Horton et al., 2014).

Growing evidence suggests that during wet conditions (Schinasi et al., 2020; Soneja et al., 2016) or thunderstorms (Grundstein et al., 2008), there is an increase in asthma-related health outcomes or outbreaks, especially in the presence of high concentrations of respirable airborne allergenic pollen during pollen seasons (D'Amato et al., 2017; D'Amato et al., 2015; D'Amato et al., 2016; Smith et al., 2022). In Philadelphia, Pennsylvania, heavy summertime precipitation was associated with an 11% increase in the odds of asthma exacerbation in children (Schinasi et al., 2020). A study conducted in Maryland found that exposure to summertime extreme precipitation events were associated with an increased risk of asthma hospitalizations (Soneja et al., 2016). ED visits for asthma in Atlanta, Georgia between 1993 and 2004 were 3% higher on days following thunderstorms when there was rainfall (Grundstein et al., 2008).

The study of molecular aerobiology is developing, and the molecular level interactions between aeroallergens, meteorological factors, and the immune system are yet to be elucidated (Cecchi et al., 2018). It is important to explore the relationship between heavy precipitation and asthma to reduce vulnerability among susceptible populations, especially with the expected increase in the frequency, duration, and intensity of extreme precipitation events in the coming decades. Precipitation can serve as a natural scrubber of allergens and particulate matter from the air (Jackson et al., 2011). Precipitation may also have the potential to negatively affect asthma prevalence by influencing concentrations, dispersion, or allergenicity of respiratory irritants or allergens. One hypothesized mechanism proposes that the osmotic rupture of pollen grains by precipitation causes the release of higher concentrations of respirable aeroallergens (Cecchi et al., 2018; Poole et al., 2019), which are known respiratory irritants. Rainfall events may also facilitate the higher concentrations of fungal spores (Rathnayake et al., 2017), which are asthma triggers. However, during light precipitation events, the particles are released in larger sizes that are less adequate for deeper lung airways penetration (Cecchi et al., 2018). We explore this non-linear relationship between precipitation and asthma in our study. The objectives of this study are to: (a) explore the association between heavy precipitation and risk of asthma ED visits in NYS by spatial and temporal linkage of meteorological data with ED visit data during non-winter months from 2005 to 2014; (b) assess precipitation thresholds by non-winter seasons at which excessive risk of ED visits occur; and (c) compare health outcome associations using spatially contiguous gridded meteorological data against monitor precipitation data.

2. Materials and Methods

2.1. ED Visit Data

ED data from non-winter months (March–November) between 2005 and 2014 were obtained from the NYS Department of Health's (NYSDOH) Statewide Planning and Research Cooperative System (SPARCS) for the entire state of New York. The identification of asthma ED visit cases was based on the International Classification of Diseases, Ninth Revision (ICD-9) principal primary diagnosis code 493.xx. Additional variables including residential address, county, age, race, ethnicity, gender, and ED visit date were obtained. Demographic distributions were assessed by age and sex. For exposure assignment, the patient's residential address was used in the absence of actual place of exposure. Asthma ED cases were geocoded to the street level to assign a latitude and longitude using locators from the Street and Address Maintenance Program (NYSGIS Clearinghouse, 2019), ArcGIS (ESRI Inc., 2019), MapMarker (Pitney Bowes, 2018) and NYCgbat (NYC Department of City Planning, 2019). US 2010 census tracts were assigned to geocoded addresses based on the census tract boundary the addresses fell within. Approvals from NYSDOH's Institutional Review Board were obtained for data use and acquisition.

2.2. Precipitation and Temperature Data

Daily total precipitation (mm), daily maximum temperature and heat index data (both in degree Fahrenheit) from 2005–2014 were obtained from the National Aeronautics and Space Administration's (NASA) North American

Land Data Assimilation System forcing data for Phase 2 (NLDAS-2) (NASA, 2021), which provides estimates of precipitation and temperature at a spatial resolution of approximately 12–14 km (1/8-degree grid). The NLDAS-2 data set integrates both observation-based and model reanalysis data executed at a grid surface with ∼14 km (1/8th degree) resolution over North America. The North American Regional Reanalysis fields that are used to generate NLDAS meteorological fields are spatially interpolated to the finer resolution of the NLDAS 1/8th-degree grid and then temporally disaggregated to the NLDAS hourly frequency (Cosgrove et al., 2003). Using a spatial join, the NLDAS grids were overlaid on the asthma case coordinates, and the precipitation and temperature value for the grid cell was assigned to the corresponding addresses based on date of admission.

2.3. Air Pollution Data

Since weather changes interact with air pollutants to influence respiratory health (Poole et al., 2019), daily predictions of daily average particulate matter 2.5 ($PM_{2.5}$) and 8 hr daily maximum ozone (O_3) were obtained from the US Environmental Protection Agency's Bayesian space-time downscaling fusion model which were available at 2010 US Census Tract level to serve as covariates (U.S EPA, 2022). Date of admission and census tract ID were used to assign air pollution values to the geocoded addresses.

2.4. Land Cover Data

We explored the use of land cover data from the National Land Cover Database (NLCD) (National Land Cover Database 2011 Land Cover (CONUS), 2011), year 2011, as a proxy for exposure to pollen and to explore differences in outdoor air pollutants in rural versus urban environments. Metrics for percentage of open space include census tract land which is deciduous, evergreen, or mixed forests, shrub/scrub, grassland/herbaceous, pasture/hay, cultivated crops, woody wetlands, barren land, and emergent herbaceous wetlands. Furthermore, developed open space and low/medium/high intensity developed land areas and open water were excluded. Percentage of open space was categorized into two classes of 0%–49.9% open space and greater than or equal to 50% open space.

2.5. Study Design and Statistical Analysis

A time-stratified semi-symmetric bi-directional case-crossover study design (Maclure & Mittleman, 2000; Wu et al., 2021) was employed to analyze the association between precipitation and asthma ED visits. The date of ED visit for asthma served as the case day, and days were selected from a 28-day stratum window, 7, 14, and 21 days before and/or after the case day, resulting in 2–4 controls per case. Discordant numbers of control days may occur as a result of some control days falling outside of the study period. The control windows need to represent the distribution of exposure when there is a risk for the outcome. They should be sufficiently close in time to maintain a similar baseline risk, yet adequately distant to ensure that the exposures are not correlated. For instance, if an asthma ED visit occurred on the last Friday of July 2010, then precipitation measures from the last Friday of July were compared to other Fridays within a 28-day stratum window of that date within 2010. This study design allowed for each case to serve as its own control, thereby controlling for non-time varying individual-level confounders such as age, race/ethnicity, sex, smoking, and sociodemographic factors. Using the same day of the week as the referent times allowed the comparison to control for day-of-the-week effects such as varying pollution exposures and individuals' routines. Long-term time trends, seasonality, and day of the week were adequately controlled through selection of control days by week and the relatively short 28-day stratum window. We used an alternate stratum window of exposure to match controls based on month of year rather than a 28-day segment, although this did not result in significant differences. To ensure that each asthma ED event is analyzed independently, recurrent asthma ED visits of the same individual within a week (washout period of 7 days) of their previous visit were eliminated.

Piecewise linear spline regression used in a conditional logistic model was applied to assess the association between precipitation and asthma. Based on modeled relationships between daily total precipitation (mm) and asthma ED visits in NYS, we established trigger points for every 10 mm increase in daily total precipitation to compare the relative sensitivity to extreme precipitation. Knots defining slope changes were sequentially selected at 10 mm intervals. Models using backward elimination (retaining p-value <0.1) to choose defining knots were assessed. We also explored the use of 5 and 25.4 mm (1 inch) intervals, and mixed bins based on the case distribution by daily precipitation totals, with intervals defined as 0–25 mm, 25–50 mm, 50–80 mm, 80–100 mm,

Table 1
Demographic Characteristics of Asthma Emergency Department Visits (ICD-9 Code: 493) by Season for 2005–2014 in New York State

Asthma ED visits	Spring	Summer	Fall	Total
Characteristics	356,696 (36.74%)	231,611 (23.86%)	382,596 (39.41%)	970,903 (100.00%)
Gender				
Female	186,665 (52.33%)	126,617 (54.67%)	199,477 (52.14%)	512,759 (52.81%)
Male	170,026 (47.67%)	104,993 (45.33%)	183,117 (47.86%)	458,136 (47.19%)
Age Group, in years				
0–4	51,697 (14.49%)	30,315 (13.09%)	70,703 (18.48%)	152,715 (15.73%)
5–17	94,177 (26.40%)	41,230 (17.80%)	100,642 (26.31%)	236,049 (24.31%)
18–24	38,701 (10.85%)	28,573 (12.34%)	43,095 (11.26%)	110,369 (11.37%)
25–44	89,724 (25.15%)	67,027 (28.94%)	91,855 (24.01%)	248,606 (25.61%)
45–64	68,058 (19.08%)	53,328 (23.02%)	63,753 (16.66%)	185,139 (19.07%)
>65	14,339 (4.02%)	11,138 (4.81%)	12,548 (3.28%)	38,025 (3.92%)

100–115 mm, 115–130 mm, 130–145 mm, 145–160 mm, and >160 mm; and found that the use of 10 mm precipitation intervals provided the most variability and ease of interpretation. As employing backward elimination did not change effect estimates, we did not use it for our final models for ease of interpretation. Along with overall non-winter analysis, threshold analyses to assess differences by season were run for spring (March 1–May 31), summer (June 1–August 31) and fall (September 1–November 30). We restricted our analysis to only non-winter months to focus on pollen season (roughly March to October) in NYS (New York State Department of New York State Departmentof Health, 2013, 2023) and removed months where the effect of cold/flu is the largest.

We explored daily varying exposures such as maximum temperature, maximum heat index, daily average concentrations of particulate matter less than 2.5μ and daily maximum $O_{3,}$ used as continuous terms, as potential confounders. Maximum heat index values were calculated for temperatures above 80°F and substituted with maximum temperature values at temperatures below 80°F (Steadman, 1979a, 1979b). Using either maximum temperature or maximum heat index did not change the effect estimates, and so our final models use maximum heat index as it takes relative humidity into consideration.

2.6. Sensitivity Analysis

To evaluate the difference in quality of exposure assignment between gridded data and monitor-based precipitation data in NYS, sensitivity analyses were conducted to compare the associations derived from the threshold analyses. Station based daily total precipitation data from 2005 to 2014 were obtained from the Global Historical Climatology Network-Daily (GHCN) database obtained from National Centers for Environmental Information (NOAA National Centers for Environmental Information, 2022). We used a subset of the GHCN data set, with 31 Automated Surface Observing System monitoring stations and 2 Climate Reference Network stations for analysis (Figure S2 in Supporting Information S1). All geocoded asthma ED visits that fell within a 10-mile buffer of a monitoring station were assigned that monitor's daily precipitation totals based on date of admission. Records that fell within two buffers were assigned to the closest monitor.

All statistical analyses were conducted using SAS statistical software version 9.4 (SAS Institute Inc., 2021) and R Studio. Geographic Information System functions were conducted using ArcGIS®.

3. Results

3.1. Descriptive Statistics

There was a total of 970,903 asthma ED cases in NYS for the period between 2005–2014 excluding winter months (Table 1). Comparing asthma ED visits by non-winter seasons in NYS, asthma ED visits were highest in the fall (39.41%), followed by spring (36.74%), and summer (23.86%). There were more females (52.81%) with

Table 2
Distribution of Meteorological Variables Categorized by Season During Non-Winter Months, New York State, 2005-2014

Meteorological variable	Minimum	Median	75th	90th	95th	99th	Maximum	Mean	SD
NLDAS Precipitation, daily total (mm)	0.0	0.1	3.0	10.5	17.3	35.4	227.1	3.3	7.6
By Season									
Spring	0.0	0.1	2.4	9.2	15.2	30.8	176.3	2.8	6.5
Summer	0.0	0.2	3.8	11.9	18.8	37.2	200.0	3.7	8.3
Fall	0.0	0.1	2.8	10.4	17.7	37.6	227.1	3.3	8.0
Maximum temperature (°F)	−9.3	64.4	74.4	80.2	83.1	87.6	102.6	61.8	15.7
Maximum Heat index (°F)	−9.3	64.4	74.4	82.0	86.9	95.1	123.9	62.2	16.5
Particulate Matter 2.5 (daily avg, μg/m^3)	0.2	8.7	13.0	18.7	22.7	31.9	81.8	10.3	6.2
Ozone (daily 8h max, ppm)	0.2	34.4	43.9	54.2	61.8	75.7	121.4	35.8	14.1

asthma ED visits than males (47.19%). In the spring and fall, children between 5 and 17 years old had the highest proportion of asthma ED visits between 2005 and 2014, followed by adults aged 25–44 years. However, in the summer, asthma ED visits were highest in the 25–44 years age group, followed by those in the 45–64 years age group (Table 1).

The daily total precipitation from NLDAS in NYS between 2005 and 2014 ranged from 0.0 to 227.1 mm during non-winter months, with highest precipitation totals occurring in the fall season (Table 2). The average daily precipitation was 3.3 mm for non-winter months and fall, and 2.8 and 3.7 mm for spring and summer seasons respectively. At the 95th percentile, precipitation amounts were at 17.3, 15.2, 18.8, and 17.1 mm for non-winter, spring, summer and fall seasons respectively. Maximum temperature and maximum heat index ranged from −9.3 to 102.6°F and −9.3 to 123.9°F respectively. The average daily $PM_{2.5}$ was 10.3 μg/m3 while daily 8-hr maximum for ozone was 35.8 ppm.

3.2. Threshold Analysis

Figure 1 shows results from the threshold analyses assessing the association between daily total precipitation from NLDAS-2 and the risk of asthma ED visits from 2005 to 2014. Risks were decreased or near unity for precipitation levels below around 50 mm. In general, we observe that risk is significantly increased (RR > 1.0) for precipitation around 50 mm and higher in non-winter months, with increased risks at higher levels of precipitation. We did not report estimates for daily precipitation totals above 130 mm as the number of cases and precipitation days were very low at such high levels. Overall, we did not observe evidence of effect modification by the covariates $PM_{2.5}$, O_3, and maximum heat index (table not shown). Additionally, we compared the threshold limit for areas with less than 50% open spaces to those with greater than or equal to 50% open spaces, as a potential indicator of pollen exposure, and observed slightly higher risks for asthma ED visits when precipitation increased from 50 to 60 mm for less than 50% open space (figure not shown). No significant increased risk was observed for open spaces greater than or equal to 50%, suggesting that use of land cover may not capture the extent of exposure to pollen.

The results suggest that seasonal differences exist in the associations between precipitation and asthma ED visits. Similar to non-winter months overall, for each season, risks were decreased or near unity for lower levels of precipitation. However, there was some variation by season in the lowest 10 mm precipitation range at which the lower bound of 95% confidence interval of relative risk of asthma ED visits was greater than 1. During the spring season, this occurred at 30–40 mm, while for summer and fall seasons, the estimates were higher at 60–70 mm and 50–60 mm, respectively, and were not always statistically significant. For spring and fall, risk estimates tended to remain elevated through higher levels of precipitation. Results for the summer were more varied.

3.3. Sensitivity Analysis

As shown in Supporting Information S1, the NLDAS tended to underestimate precipitation when compared to GHCN ground observations (comparing Table 2 to Table S1 in Supporting Information S1). Approximately 16% of cases did not fall inside any of the buffers surrounding the selected GHCN stations and thus were excluded.

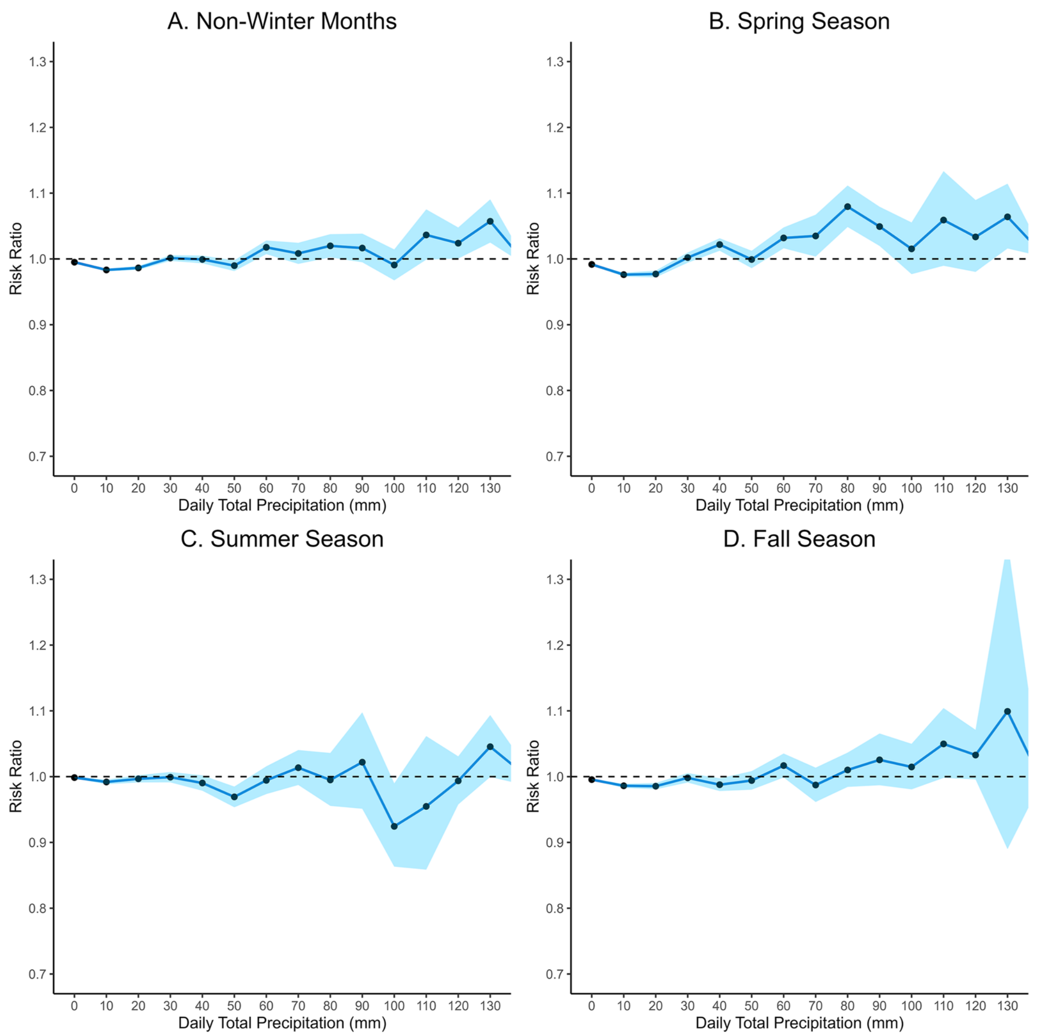

Figure 1. Risk Ratios and 95% Confidence Intervals (represented by blue bands) for associations between NLDAS-2 Daily Total Precipitation and the Risk of Asthma emergency department Visits in New York State, between 2005 and 2014, adjusting for Maximum Heat Index, $PM_{2.5}$ and O_3.

There were some differences in the risk patterns with increasing levels of precipitation when using the GHCN observations compared to the NLDAS estimates. In the non-winter months overall, the threshold precipitation level at which significant risk of asthma was observed using the GHCN monitor precipitation data was higher (70–80 mm) than that observed using NLDAS data (50–60 mm). During the summer season, statistically significant risk estimates at precipitation totals between 70 and 90 mm were observed when using GHCN data (Figure S1 in Supporting Information S1), but not when using NLDAS data. This illustrates the sensitivity of our results to the source of precipitation data utilized in the models.

In our statewide analysis spanning a 10-year study period in NYS, there was some evidence of an association between heavy precipitation and risk of asthma ED visits. There was some evidence of seasonal effects, with the strongest association seen during spring season. Similarly, previous studies have shown associations between heavy precipitation and the risk of asthma hospitalization (Soneja et al., 2016), and asthma exacerbations, ED, and outpatient visits (Schinasi et al., 2020); and following major thunderstorms where the risk of asthma attacks was observed (Anderson et al., 2001; D'Amato et al., 2019; Dabrera et al., 2012; Grundstein et al., 2008; Murray et al., 1994). However, there were some differences in the estimated risk curves depending upon the source of precipitation exposure data, as shown in the sensitivity analysis.

In the threshold analyses assessing the association between daily total precipitation from NLDAS-2 and the risk of asthma ED visits, increased risk of asthma ED visits was observed when precipitation increased above

50 mm during non-winter months as the associations remained mostly elevated at higher levels of precipitation (Figure 1). Seasonal differences exist; with increased risk in spring occurring at precipitation levels as low as 30 mm, compared to fall at 50 mm. The lower trigger range in the spring season may be related to allergenic availability (Schinasi et al., 2020) of grass and tree pollen which have overlapping seasons in spring in NYS (New York State Department of New York State Departmentof Health, 2013, 2023). A Philadelphia based study found asthma exacerbations to be strongest when tree pollen counts were highest (Schinasi et al., 2020). They observed odds ratios of 1.05 (95% CI: 1.00, 1.09) during spring, and 0.97 (95% CI: 0.93, 1.01) during autumn, when classifying their extreme precipitation threshold at the 90th percentile based on a 30-year baseline (Schinasi et al., 2020). Reasons for seasonal differences may be that in summer months, NLDAS underestimates precipitation (compare Table 2 to Table S1 in Supporting Information S1), differences in pollen availability, and/or people's activities. A New York City based study concluded that tree pollen which peaks in mid-spring had significant association with asthma exacerbations (Ito et al., 2015). These seasonal differences highlight the roles of seasonally varying allergens (e.g., pollen and mold), and behavioral patterns.

4. Discussion

The results of our analysis have also been suggested in other studies that classified exposure to precipitation using relative thresholds. The case-crossover study based in Philadelphia estimated the association between summertime (June through August, 2011–2016) daily heavy precipitation and asthma exacerbations among children and observed an 11% increased risk on days with mean daily precipitation above the 95th percentile (0.98 inches or 24.89 mm) versus no precipitation days (Schinasi et al., 2020). When restricted to ED visits, the odds were 20% higher. The equivalent of the 95th percentile precipitation for summer months in our study is at 19.3 mm (GHCN; Table S1 in Supporting Information S1) and 18.8 mm (NLDAS; Table 1), and we observed an elevated risk of 3% (GHCN; Figure S1 in Supporting Information S1) and 1% (NLDAS; Figure 1) when precipitation amounts increased from 70 to 80 mm. Similarly, a Maryland based study found an 11% increased risk of hospitalizations for asthma was associated with extreme precipitation during summer (Soneja et al., 2016).

In our study, the 90th and 95th percentiles of total daily precipitation for non-winter months and all seasons were lower than the precipitation ranges at which the first positive statistically significant associations were observed. Classifying the exposures using slope changes at 10 mm precipitation intervals within a continuous model enabled the illustration of variability in the associations between a wide range of precipitation totals and asthma ED visits. For instance, we observed positive associations when daily precipitation totals were higher, but those associations did not increase exponentially or remain constant with increased precipitation. The decreased risk and wider confidence interval of risk observed at precipitation totals higher than 130 mm may reflect the lack of GHCN data for 16% of cases in our data set as well as lower number of days with precipitation above 40 mm. Note that the 99th percentiles for GHCN and NLDAS precipitation data were 38.1 and 35.4 mm respectively. Our results suggest that using common absolute (i.e., 1 inch, 2 inches etc.) or relative (90th percentile, 95th percentile etc.) thresholds could possibly wash out the effects of precipitation at amounts where risk may be elevated.

To contextualize the thresholds, according to the American Meteorological Society, the intensity of rainfall at any given time or place is classified as “light” when the rate of fall varies between trace and 2.5 mm per hour, and the maximum rate of fall is no more than 0.25 mm in 6 minutes. “Moderate” rain is classified as 2.6–7.6 mm per hour with the maximum rate of fall no more than 0.76 mm in 6 minutes. “Heavy” rain is classified as more than 7.6 mm per hour or more than 0.76 mm in 6 minutes (AMS, 2012). In NYS, the precipitation intensity per hour is approximately 2.29 mm/hr in a 24-hr period (NRCC & NRCS, 2022a) while the 24-hr extreme precipitation estimate is 52.8 mm (95% CI 49.0, 55.9 mm) (NRCC & NRCS, 2022b). The total annual precipitation for any given area of NYS ranges from approximately 783.1 mm to 1,719.6 mm (NYS Mesonet, 2023b), while the 24-hr precipitation ranges from 0.00 to 60.71 mm (NYS Mesonet, 2023a). The National Weather Service (NWS) monitor in New York City's Central Park reports the total seasonal average precipitation from 2005 to 2014 to be 346.3 mm in the spring, 403.3 mm in the summer, and 329.4 mm in the fall (NWS, 2021). For the same time period, the NWS monitors in Buffalo, NY reports a total seasonal average of 218.8 mm during spring, 274.8 mm during summer, and 318.1 mm during the fall (NWS, 2023).

The reasons for differences in asthma ED visits by age group are unclear, but a plausible explanation might be that 5–17-year-old children are a biologically vulnerable age group and might be more likely to be outdoors in milder weather during the spring and fall. These seasons may also have increased allergenic availability due to high pollen counts. Springtime increases in pediatric asthma exacerbations have been associated with increased outdoor allergens, particularly tree allergens (Ito et al., 2015), while the exacerbations in the fall season have been associated with sensitization to common indoor allergens such as dust mite, cockroaches, and rodents resulting from increased time spent indoors (Teach et al., 2015). Additionally, during the fall season, children return to school and may be exposed to other viruses that are typically prevalent in this population and may trigger asthma exacerbations (Cochran et al., 2022; Lin et al., 2011). The higher asthma ED visits during the summer in the 25–44 year olds may be attributed to various environmental triggers such as extreme heat, occupational exposure, strenuous recreational activities, etc. Similar trends were observed in a previous study assessing seasonal trends in NYS asthma-related hospital admissions from 1995 to 2006 (Lee et al., 2012). Increased ARHAs in the spring and fall seasons were observed with lower rates in the summer season for both under- and over-18 year olds (Lee et al., 2012).

Most epidemiological studies in the past have relied on land-based observation stations and ambient air monitoring networks to estimate human exposure to meteorological variables. Since both precipitation and temperature have considerable spatio-temporal variability, the use of the spatially and temporally contiguous meteorological gridded remote NLDAS-2 data in our study provide a means of addressing the gaps in exposure classification from the meteorological station networks. The strength of the NLDAS-2 data set is that it integrates both ground observations and modeled reanalysis data. If there is sufficient spatial coverage, studies based on ground-based monitors should be reliable. While land-based observations are highly valuable in stating ground reality and represent total precipitation at a particular location, they may be affected by the environment in the immediate vicinity of the monitor. Monitor gauges may miss extreme precipitation totals that may be within a relatively short distance away (Krajewski et al., 2003; Sieck et al., 2007). Similarly, a limitation of the NLDAS-2 precipitation data is that they are presented on an approximately 14 × 14 km area grid, which may result in smoothing total precipitation within the area and potentially lead to loss of extremes and precision as precipitation levels could vary substantially within that area. Overall, for climate and health research, the adoption of "hybrid" data sources such as NLDAS-2 which integrates satellite-based reanalysis data and monitor data, provide spatially and temporally refined exposure-response functions, and offer insight into areas with sparse monitor observations which were previously unaddressed (Adeyeye et al., 2019). The time frame of 2005–2014 was selected as the NYS SPARCS ED data set became available starting 2005, and is consistently reported using ICD-9 in the study period. We chose 2014 as the natural end of the data set to avoid misclassification due to the transition to ICD-10 in 2015. We plan on replicating the study from 2015 onwards for a future analysis.

Heavy precipitation and thunderstorms are associated with asthma epidemics in several countries, especially those with high aeroallergen loads (Andrew et al., 2017). Notably, in Australia in 2016, the largest global outbreak of thunderstorm asthma resulted in a 42% increase in the caseload of emergency services and a 432% increase in ED visits for acute respiratory distress (Andrew et al., 2017). Similarly, a recent study assessing the association of asthma ED visits with precipitation and temperature on thunderstorm days observed a significant association with higher daily mean precipitation (RR 1.145 per 1 g/m2; 95% CI: 1.009, 1.300) and lower daily mean temperature (RR 1.011 per 1°C change; 95% CI: 1.000, 1.021) (Park et al., 2022). "Thunderstorm asthma" is the terminology used to describe an observed increase in cases of acute bronchospasms following a thunderstorm. While our study did not assess thunderstorm events specifically, there is conceivably significant overlap between days with heavy precipitation and thunderstorms. Although thunderstorm-associated asthma epidemics are sporadic, with the projected increase in frequency of heavy precipitation events and thunderstorms there may likely be an uptick in asthma associated with heavy precipitation events in NYS.

Precipitation may also act as a natural scrubber of allergens (Schramm et al., 2021) and air pollutants from the atmosphere, and studies have found a negative correlation between precipitation and $PM_{2.5}$ (Ouyang et al., 2015). In our study as well, we observed protective effects of precipitation at levels below 20 mm overall and by seasons. Mechanistically, the size and carrier of allergens serve as crucial factors influencing allergic sensitization and exacerbations (Cecchi et al., 2018). Recent findings on bioavailability of allergens have raised hypotheses that suggest that rain or humidity may hydrate pollen grains and cause mechanical and/or osmotic rupture of the grains, resulting in the release of respirable allergenic aerosols which could induce asthma in sensitive populations (Cecchi et al., 2018; Poole et al., 2019). A recent study based on high-speed imaging shows that during heavy rain and/or thunderstorms the raindrops precipitate and hit the ground, and the effect is strong enough that generated water jets break up to release bioaerosols possibly containing allergens (Cecchi et al., 2018). The fine size of the particles allows for deeper penetration of allergens in airways to induce asthma attacks. During light precipitation events, the large sizes of the released aeroallergens are less adequate to respire deeper into the lung's airways (Cecchi et al., 2018), which possibly explains why we do not observe increased risk of asthma ED visits at lower levels of precipitation in our study. The findings that microdroplets of approximately 5 μm can carry allergens, provide an explanation for thunderstorm related asthma and the associated mechanisms of pollen-induced asthma (Cecchi et al., 2018). In addition, the relationship between known asthma triggers such as aeroallergens, pollens, and air pollutants with precipitation and other meteorologic factors is complex (Roldán-Henao et al., 2020; Tian et al., 2021). As such, these environmental triggers may serve as potential mediators and/or modifiers in the exposure-outcome pathway between precipitation and asthma. We observed a statistically significant positive correlation between census tract estimates of ozone and $PM_{2.5}$ (~36%) and a modest yet statistically significant negative correlation between precipitation and ozone (11.3%) /$PM_{2.5}$ (6%) in our data. Given this observed correlation between precipitation and air pollutants ($PM_{2.5}$ and ozone), the results presented in the study may be partly representative of the underlying associations between air pollutants and asthma. Although beyond the scope of this study, further exploration of these effects (direct or indirect) using data at finer spatial resolution is recommended.

The strengths of this study include the use of a large statewide data set and employing a case crossover study design which controls for non-time varying individual-level confounders such as underlying comorbidities, age, race, sex, smoking, and sociodemographic factors thereby minimizing bias introduced by these factors. The use of the gridded NLDAS data provided complete spatial coverage for NYS and fine scale resolution. Therefore, the NLDAS data set provides a means of addressing exposure misclassification issues present in the use of monitor data with limited spatial coverage. Additionally, the use of precipitation intervals for exposure metrics in the threshold analysis illustrates the variability of the associations.

There are some limitations that should be considered when interpreting our findings. In the sensitivity analysis, the pattern of estimated risks of asthma from increasing precipitation were different when GHCN observations were used. The use of GHCN monitor data to assign exposure led to a loss of about 16% of cases as compared to using gridded estimates, which might contribute to the shape of the curves at extreme precipitation values where the counts for cases were low. In some cases, GHCN results are likely impacted by sparser data, indicated by wider confidence intervals at some precipitation levels leading to potential misclassification. While we do not believe this misclassification would differentially bias the results, it is a reminder that they should be interpreted with caution. In addition, the use of asthma ED visits is not representative of the general asthmatic population. Rather, it reflects differences in access to care; and the results may not be generalizable to all asthmatics. The use of residential addresses for exposure assignment may not be reflective of the actual place of exposure, thereby leading to exposure misclassification. We also lack information on behaviors that may limit exposure to heavy precipitation events and allergens. When using clinical data, the time of ED visit does not reflect time of event, and the use of total daily precipitation data does not always reflect precipitation intensity of whether the precipitation event occurred over a few hours or the entire day. The modifying effects of other meteorological variables such as thunderstorm, relative humidity, wind speed and atmospheric pressure were not assessed in this analysis. Our model did not show any evidence of increased risk at lower levels of precipitation. However, assessment of drought conditions is beyond the scope of this project. Pollen concentrations at the time of exposure were accounted for as the statewide pollen monitoring system is sparse. Land cover was used as a proxy for potential exposure to pollen, due to sparse availability of the pollen data in NYS. Previous studies have described associations of pollen counts with changes in land-cover patterns (Emberlin et al., 1993, 1999; McLauchlan et al., 2007). A study similar to ours conducted in Philadelphia did not observe any effect modification by area-level measures including land cover, where LIDAR and NLCD data were employed (Schinasi et al., 2020). Land-cover has also been shown to be a significant predictor of various pollen allergens including tree, grass, weed and Acer (Dellavalle et al., 2012). However, different land covers produce different mixes of pollens, including from grasses and weeds in varied quantities, which may vary by season. The lack of a comprehensive pollen data source in the study area prevents further exploration of the impacts of pollen on the associations between heavy precipitation and asthma-related ED visits in this study in NYS. This limitation supports the need for better quality pollen data, especially in the context of climate change.

Our study findings add to the literature related to meteorological parameters such as precipitation and temperature (Adeyeye et al., 2019) and the risk of adverse health outcomes by quantifying the effects of heavy precipitation on asthma. This research contributes to a less well understood part of the literature regarding risk factors for asthma exacerbations since the association between asthma and heavy precipitation is not well explored and in most cases not even considered as a risk. More research is needed to better understand precipitation as a risk factor, but the results could inform local health departments' targeted awareness campaigns to vulnerable populations, and clinicians could include heavy precipitation as a potential environmental trigger to be aware of when speaking with asthma patients. In the context of climate change, these findings are relevant to identify appropriate public health intervention strategies as extreme weather events continue to increase in the coming decades.

5. Conclusions

Our findings suggest that heavy precipitation above around 50 mm may be associated with small increased risks of asthma ED visits in NYS, with varying seasonal effects. The use of gridded meteorological data provides a way to address exposure misclassification through rich spatial coverage. To confirm and extend this research, exploration of potential underlying multi-factorial mechanisms and modifiers is needed and should be expanded to other geographical areas. This analysis contributes to the body of research about the impacts of weather on health and has implications in the context of climate change where NYS is expected to have wetter weather in the decades to come.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Data for this research came from the NYS Statewide Planning and Research Cooperative System (SPARCS) database. This data is not publicly available as it would compromise individual privacy.

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