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Research article

Characterizing pediatric discharge diagnoses associated with daily extreme heat exposure in the Midwestern US: A retrospective case-crossover study

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A R T I C L E I N F O

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A B S T R A C T

Aim: To explore the association between daily extreme heat exposure (daily mean temperature is greater than the 90th percentile for the month) and pediatric (birth to 18 years old) urgent care clinic, emergency department, and inpatient hospitalization discharge diagnoses for any causes and 12 individual morbidities of interest.
Design: A time-stratified, case-crossover study design.
Methods: We analyzed discharge diagnoses from the Saint Louis University-Sisters of St. Mary, a non-profit healthcare system in the United States, using the Virtual Data Warehouse. Our analysis encompassed urgent care clinic visits, emergency department visits, and hospitalizations within a Midwestern healthcare network across Missouri, Wisconsin, the Oklahoma City metropolitan area, and Southern Illinois, in the United States. Our study focused on all causes and examined 12 specific morbidities of interest. We focused on pediatric patients during the warm season months of May through September in 2017–2022. For all outcome models, an overall model was calculated and then each model was stratified by age, sex, race, and neighborhood socioeconomic status, excluding strata with unknown values.
Results: We found significant associations with dehydration, general symptoms, heat-related illnesses, and infections. The impact of extreme heat exposure varied across demographics, with vulnerable groups including children aged one to four, males, and individuals from low socioeconomic status areas.
Conclusions: Our findings highlight important opportunities for health promotion in communities and preschools. Better informing caregivers of the risks and implementing policy level initiatives may help reduce pediatric exposure to extreme heat. Future research should focus on longitudinal studies to explore these dynamics further and develop effective heat mitigation strategies to protect vulnerable pediatric populations from the adverse effects of extreme heat.

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1. Introduction

Globally, extreme heat is increasingly concerning due to its rising frequency, intensity, and duration, significantly impacting human health [1]. Extreme heat exposure involves prolonged elevated temperatures or humidity exceeding regional averages [2]. In 2023, the United States experienced record-high temperatures, leading to an increase in emergency room visits for heat-related illnesses, with vulnerable groups such as children, pregnant women, outdoor workers, and individuals with pre-existing medical conditions being disproportionately affected [3]. Children are highly susceptible to extreme heat due to developing thermoregulatory systems, higher body surface area, fewer sweat glands, and higher metabolic rates [4,5].

Despite well-documented risks of extreme heat exposure for adults [6], research on children's specific risks from extreme heat exposure is lacking [5,7,8]. A 2023 scoping review found associations between high temperatures and pediatric health issues worldwide, including heat-related illnesses, dehydration, diarrhea, infectious diseases, asthma, and injuries [5]. However, research on susceptibility by pre-existing conditions is limited, with substantial evidence only for cystic fibrosis [5].

Research into the health impacts of extreme heat is crucial for enhancing pediatric care and developing effective strategies to help children adapt to rising temperatures [5,7]. More studies are needed on how heat exposure affects children's healthcare utilization and discharge diagnoses [3,7]. Currently, there is limited research on pediatric heat-related morbidity in the Midwest [3,7], a region with unique environmental factors such as humidity and urban heat islands, which differ significantly from other parts of the United States [9]. Socioeconomic status, racial or ethnic background, and chronic health conditions also play a role in determining a child's vulnerability to heat [7]. Further research is necessary in under-studied regions like the Midwest and on factors contributing to heat vulnerability [7]. Understanding these dynamics is essential for informing health services and interventions to mitigate the effects of extreme heat on vulnerable populations, especially children [5,7].

To address this gap, our study aimed to explore the relationship between daily extreme heat exposure and pediatric healthcare outcomes. We defined extreme heat exposure as days when the daily mean temperature exceeds the 90th percentile for that month. This threshold was selected due to its broad acceptance in previous research examining the effects of extreme heat on health outcomes in adults and children [7,10–14]. These outcomes include acute care visits (urgent care visits, emergency department visits, and inpatient hospitalizations) for any reason. In the United States, urgent care centers are walk-in clinics that address minor injuries and illnesses, offering a convenient alternative to emergency rooms for non-life-threatening conditions [15]. Emergency departments, on the other hand, are hospital units designed for quick patient assessment and treatment. In emergency departments, healthcare providers determine whether patients need further tests, hospitalization or can be safely sent home [15].

Additionally, we examined 12 specific morbidities identified by ICD-10-CM (International Classification of Diseases, Tenth Revision, Clinical Modification): asthma, cardiovascular disease, dehydration, diabetes, diarrhea, general symptoms, heat-related illnesses, infections, injuries, mental/psychiatric illnesses, renal disease, and respiratory disease (Appendix 1- Table 1). Our analysis covered both general and specific health outcomes, categorizing them accordingly. Previous research on extreme heat-related healthcare utilization suggests that relying solely on primary discharge diagnoses may underestimate some admission increases [16,17]. To mitigate this issue, we categorized morbidity outcome data consistent with categories used in past studies on pediatric extreme heat-related hospitalizations [7].

The primary objective of our study was to determine the risk of pediatric morbidity associated with extreme heat exposure by analyzing the frequency of discharge diagnoses across different acute care settings (urgent care visits, emergency department visits, and inpatient hospitalizations). We hypothesized that extreme heat exposure increases the likelihood of pediatric patients' discharge

Table 1
Descriptive comorbidity characteristics of pediatric patients ≤18 years old with an emergency department, inpatient or urgent care admission from May to Sep 2017–2022 (n = 350,675 patients; 844276 visit days)[a].

	% of patients who had visits for any cause	n	# case days
Specific comorbidities			
Asthma	4.5	15,691	21,008
Cardiovascular diseases	1.7	6015	6986
Dehydration	1.6	5565	5860
Diabetes	0.4	1413	2316
Diarrhea & digestion disorders	9.6	33,792	38,614
General symptoms	15.8	55,346	63,700
Heat-related illness	0.1	464	467
Infections	2.5	8603	8982
Injury	25.6	89,857	103,300
Mental health disorders	0.7	2275	2609
Renal disease	3.0	10,627	12,123
Respiratory disease	23.9	83,892	108,571
Patients who had visits for at least one of the comorbidities of interest	**58.5**	**205,054**	——
Patients who had visits for any cause except the comorobidites of interest	**41.5**	**145,621**	———

[a] The main sample is 350,675 pediatric patients with an emergency department, inpatient or urgent care admission for any cause (all-cause) from May to Sep 2017–2022. The percentages in column 2 will not add to 100 % as a) 58.5 % of patients had one of these admissions for at least one of the 12 specific listed comorbidities, therefore, 41.5 % of patients had an admission for a comorbidity NOT specifically listed; b) the comorbidities are not mutually exclusive as patients could have had multiple admissions for different, specific comorbidities.

diagnoses across different acute care settings for conditions such as heat-related illnesses and dehydration/electrolyte imbalances.

The second objective of our study was to examine how patient demographics and morbidities might exacerbate the health effects of extreme heat exposure on children. We hypothesized that the impact of extreme heat exposure on acute care discharge diagnoses would vary by demographic factors such as age, sex, race, and neighborhood socioeconomic status (nSES).

2. Methods

2.1. Study design, participants, and setting

A time-stratified, case-crossover study design was used to analyze discharge diagnoses. This analysis encompassed acute care visits (urgent care visits, emergency department visits, and inpatient hospitalizations) within a Midwestern healthcare network across Missouri, Wisconsin, the Oklahoma City metropolitan area, and Southern Illinois, all located in the United States. We focused on pediatric patients, ranging from birth to 18 years old, during the warm season months of May through September in 2017–2022 [18]. In this design, all case days were found for each eligible patient (i.e., days a morbidity occurs in an urgent care, inpatient, or emergency department setting) from May to September in 2017–2022, and "control" or non-case days were selected based on the same day of the week in the same month and year. This design addressed time-invariant confounding of both observed and unobserved variables as patients serve as their own controls. The unit of observation was visit or "case" days. Each month serves as a stratum window, and this method compares extreme heat exposure on case days to control days, which were the same days of the week in the same calendar month that were ± 7, ± 14, and ± 21 days from case days to ensure that control days were for the same season, month, and day of the week [6,18]. Thus, there were three or four control days per patient for every given case day. Case days within seven days of each were considered the same "case period" and the first day in that period was chosen as the "case day". Employing this design, there were 13 separate case-crossover analytic datasets: one for all-cause acute care visits and one for each of the morbidities listed in Table 1 that occurred in acute care settings.

To conduct this retrospective case-crossover study, we examined de-identified medical record data obtained from the Saint Louis University-Sisters of St. Mary (SSM), a non-profit healthcare system in the United States, using the Virtual Data Warehouse. The Virtual Data Warehouse captures clinical encounters from academic and non-academic ambulatory and inpatient settings in the Midwest. The healthcare system includes rural and urban settings from the St. Louis, Missouri, metropolitan area; mid-Missouri; Southern Illinois; Oklahoma City metropolitan area; and southern Wisconsin. The Virtual Data Warehouse includes over five million patients from birth to >90 years of age who have utilized services in the healthcare system from January 1, 2008 to the present and is updated monthly. As a member site of the Health Care Systems Research Network, we define Virtual Data Warehouse variables in accordance with the network's specifications. Virtual Data Warehouse variables include the type of healthcare encounter (e.g., ambulatory, inpatient, urgent care, emergency department, etc.) with dates, diagnostic and procedure codes with dates, provider and clinic type, laboratory orders and results, vital signs, pharmacy orders, and demographics (e.g. patient age, race, sex, zip code).

In the SSM Virtual Data Warehouse, there were 530,094 pediatric patients (age 0 to 18) who utilized healthcare services (e.g., pediatric ambulatory office visits, urgent care visits, emergency department visits, or inpatient hospitalizations) between May to September in 2017–2022.

Inclusion criteria: From the overall base sample of over 500,000 pediatric patients available in the virtual data warehouse, 13 separate case-crossover cohorts of patients were created based on all-cause (i.e. any visit diagnosis) acute care visits (n = 350,675 patients), and each of the 12 morbidities listed in Table 1 (see Table 1 for sample sizes). For each morbidity, different cohorts were created for patients who visited acute care settings between May and September of 2017–2022 and who had the diagnostic codes defining each morbidity at acute care settings. Eligible case days were included if patients were 0–18 years of age.

Exclusion criteria: Patients >18 years old at eligible case days and patients not visiting the urgent care, emergency department or having an inpatient hospitalization for conditions of interest.

2.2. Outcome measures

We focused on the acute and severe exacerbations of pediatric morbidities in the summer months. Outcomes defined on case days included acute care visits for all-causes (i.e. any diagnosis present) and 12 individual morbidities defined by ICD-10 diagnostic codes (Appendix 1).

2.2.1. Exposure

Using geospatial technology, we gathered daily mean temperature data at the 5-digit zip code level in the Midwest from the PRISM Climate Group at Oregon State University. The PRISM daily temperature data are continuous-coverage grids for the contiguous United States that are derived from weather stations, climate models, topographic data, land cover data, and satellite-based temperature models that result in high-accuracy products [19]. The summary information for each month and year included in the study for patient zip codes is found in Appendix 1 – Table 2. We have identified the 90th percentile value among the daily average temperature for each zip code and calendar month. Eligible case and control days in each case-crossover cohort were defined as "extreme heat" if the daily temperature for the particular day was >90th percentile for the daily mean temperature of the respective calendar month and patient zip code. The 90th percentile was selected as the threshold to define extreme heat exposure due to frequent use in previous studies assessing the effect of extreme heat exposure on health outcomes [7,20]. We focused on the immediate, same day (i.e. lag 0) effects of extreme heat on healthcare utilization for the morbidities of interest. Prior literature has shown that the strongest effects of extreme

Table 2
Demographic characteristics of eligible patients for each case-control cohort.

	All-cause	Asthma	Cardiac	Dehydration	Diabetes	Diarrhea	General symptoms	Heat-related illness	Infection	Injury	Mental	Renal	Respiratory
	N = 350675	N = 15691	N = 6015	N = 5565	N = 1413	N = 33792	N = 55346	N = 464	N = 8603	N = 89857	N = 2275	N = 10627	N = 83892
	%	%	%	%	%	%	%	%	%	%	%	%	%
Sex													
- Female	49.3	43.3	48.3	52.4	54.6	50.9	50.7	39.2	51.4	45.6	52.7	83.7	48.6
- Male	50.8	56.7	51.7	47.6	45.4	49.1	49.3	60.8	48.6	54.4	47.3	16.3	51.4
Race													
- White	66.0	43.0	62.7	64.0	62.5	58.4	59.6	69.2	67.5	64.9	52.1	68.7	57.4
- Black	20.9	46.9	27.4	25.0	30.9	29.6	27.0	19.6	21.4	24.4	39.3	21.6	30.8
- Other	7.7	8.0	5.8	6.9	5.1	8.1	8.2	8.8	7.8	7.5	5.4	7.3	7.9
- Unknown	5.5	2.2	4.1	4.1	1.6	3.9	5.2	2.4	3.4	3.2	3.2	2.5	3.9
Age at the first case day													
- <1 years	15.3	2.0	21.5	16.2	0.4	18.9	19.4	2.4	6.9	4.7	0.0	7.9	14.1
1 to 4 years	24.2	24.2	12.2	33.2	4.5	26.6	31.2	6.5	22.9	25.4	0.6	15.4	32.9
5 to 11 years	30.1	35.4	19.7	17.8	23.9	24.6	21.6	22.0	41.1	32.0	29.0	24.8	27.8
12 to 18 years	30.3	38.4	46.6	32.8	71.3	29.9	27.9	69.2	29.1	37.9	70.4	51.9	25.2
nSES[a]													
- Unknown	0.9	0.7	0.7	0.9	0.5	0.8	1.6	1.3	0.7	0.8	1.0	0.7	0.7
- Low	43.3	58.6	54.4	52.5	53.4	53.3	50.8	46.3	45.8	47.8	53.1	50.9	49.5
- High	55.8	40.7	44.9	46.6	46.1	45.9	47.6	52.4	53.5	51.5	45.9	48.4	49.8

[a] Neighborhood socioeconomic status (nSES) from a previously validated method.(Roblin, 2013).

heat are mostly immediate and primarily observed on the same day, with some observing effects on lag day 1, with effects diminishing after lag day 1 [6,21–25].

2.2.2. Demographics

Demographic variables included age at case day visit (<1 year, 1–4 years, 5–11 years, 12–18 years); race (white, black, other, unknown); and sex (male, female). We also included an estimate of nSES from a previously validated method [26]. The nSES was computed by linking each patient's 5-digit zip code to the following variables from the American Community Survey 5-year estimates: 1) percent of households with income below poverty level; 2) percent of households receiving public assistance; 3) percent of households with annual income < $35,000; 4) percentage of adult males 20–64 years old not in the labor force; 5) percentage of adults ≥25 years old with less than a high school education; 6) log median household income; and 7) log median value of single family homes. A principal components analysis was conducted on all United States zip codes using seven specific metrics. This analysis generated a standardized factor score for each zip code, with higher scores indicating lower neighborhood socioeconomic status (nSES). The distribution of these scores across all zip codes was used to categorize areas into high nSES (scores at or below the median) and low nSES (scores above the median).

2.3. Statistical analysis and confounders

SAS v9.4 (SAS Institute, Cary, NC) was used for all analyses. Patient-level descriptive statistics (frequencies and percents) for demographic variables were calculated within each case-crossover cohort. Outcome analyses were conducted on each of the 13 visit level data sets containing eligible case and control days per patient (i.e. unit of analysis was visit day). To evaluate the effect of same-day extreme heat exposure on each outcome (all-cause and each individual level morbidity), we conducted 13 separate patient-stratified, conditional logistic regression models. These models were used to calculate odds ratios and 95 % confidence intervals. For all outcome models, an overall model was calculated and then each model was stratified by age, sex, race, and nSES, excluding strata with unknown values. An interaction term of each of these demographic characteristics and the extreme heat exposure for each model assessed whether the effect of extreme heat exposure on each outcome was different based on the demographic characteristic ($p < 0.05$ signifies a significant interaction).

2.4. Ethical considerations

The Saint Louis University Institutional Review Board deemed this work to be non-human subjects research because data were retrospective and de-identified. This study was conducted in accordance with the 1964 Helsinki Declaration [27]. Additionally, Ruppar [28] suggested using the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) checklist for observation studies. Therefore, we used the STROBE checklist (Appendix 2).

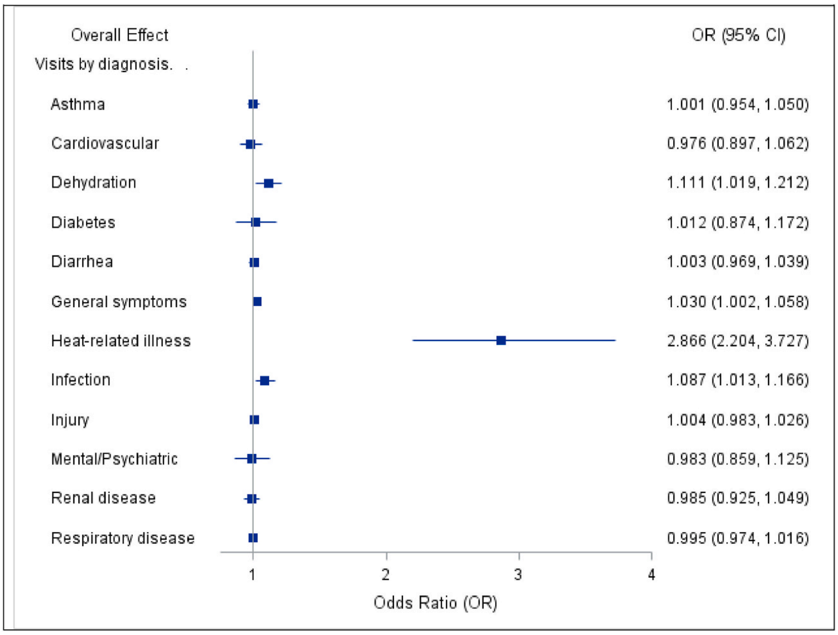

Fig. 1. Forest Plot of overall estimates of the association between extreme heat exposure and pediatric morbidities seen in urgent care visits, emergency department visits, and inpatient hospitalizations.

3. Results

Table 1 shows the breakdown of morbidities among the 350,675 pediatric patients with all-cause acute care patient visit from May through September 2017 to 2022. There were 350,675 unique pediatric patients who utilized urgent care, inpatient, and emergency department services for any cause (all-cause); of these patients, 58.5 % had at least one of the specific 12 comorbidities of interest. Also, among all patients, the most prevalent morbidities included injury (25.6 %) and respiratory disease (23.9 %), while the least prevalent were diabetes (0.4 %) and heat-related illness (0.1 %). Table 2 presents the patient-level distribution of demographic characteristics within each case-crossover cohort. The all-cause cohort was predominately White (66.0 %), at least four years old (60.4 %), and mostly from a high nSES zip code (55.8 %). There was a fairly equal distribution of males and females in the all-cause cohort (females: 49.3 %; males: 50.8 %).

3.1. Regression models

In the results of the overall conditional logistic regression models for each case-crossover cohort (Fig. 1), extreme heat exposure was associated with higher odds of dehydration (OR [95%CI]: 1.111 [1.019, 1.212]); general symptoms (OR [95%CI]: 1.030 [1.002, 1.058]); heat-related illness (OR [95%CI]: 2.866 [2.204, 3.727]); and infection (OR [95%CI]: 1.087 [1.013, 1.166]). Extreme heat exposure was not associated with any other morbidity.

3.2. Stratified analyses

In the stratified analyses, sex, age, race, and nSES heterogeneously affected the associations between extreme heat exposure and morbidities. Figs. 2 and 3 show the results of stratified conditional regression models for significant interactions with extreme heat exposure. Appendices 3 to 6 show all stratified estimates. Figures and results focus on significant subgroup differences in outcomes.

3.2.1. Age-specific associations (Fig. 2)

The effect of extreme heat exposure on all-cause acute care visits significantly differed by age ($p = 0.0112$). Specifically, there was no effect of extreme heat exposure on all-cause acute care visits for patients 1–4, 5–11 or 12–18 years old. However, for children <1 years old, extreme heat exposure was associated with a 3 % lower odds of acute care visits for any causes (OR [95%CI]: 0.969 [0.946, 0.992]). The effect of extreme heat exposure and acute care visits for general symptoms also differed by age ($p = 0.0479$). Extreme heat exposure was not associated with visits for general symptoms for children <1 year old, 5–11 years old, or 12–18 years old. However, among children, 1–4 years old, extreme heat exposure was associated with an 8 % higher odds of acute care visits for general symptoms (OR [95%CI]: 1.081 [1.031, 1.134]).

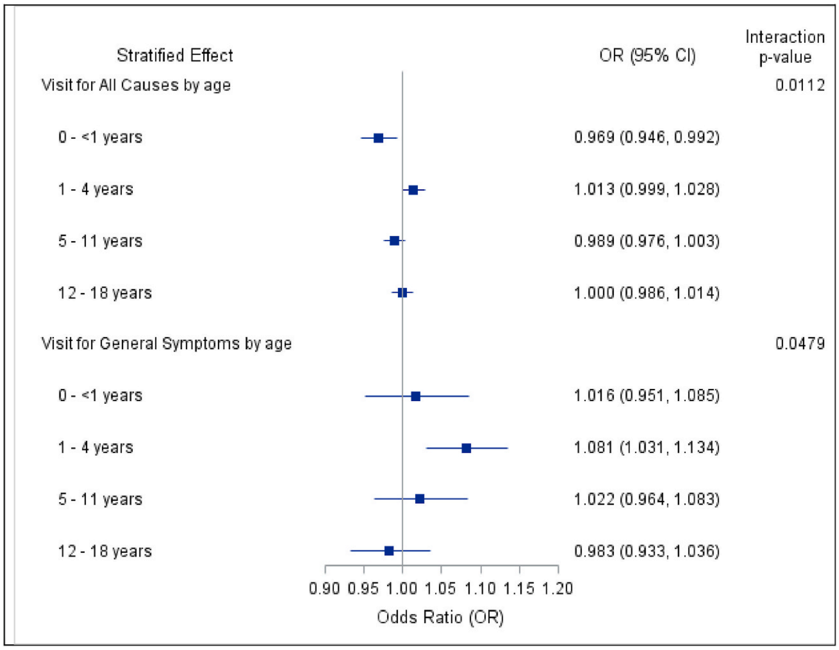

Fig. 2. Forest Plot of stratified estimates of the association between extreme heat exposure and visits for all causes and visits for general symptoms by age seen in urgent care visits, emergency department visits, and inpatient hospitalizations.

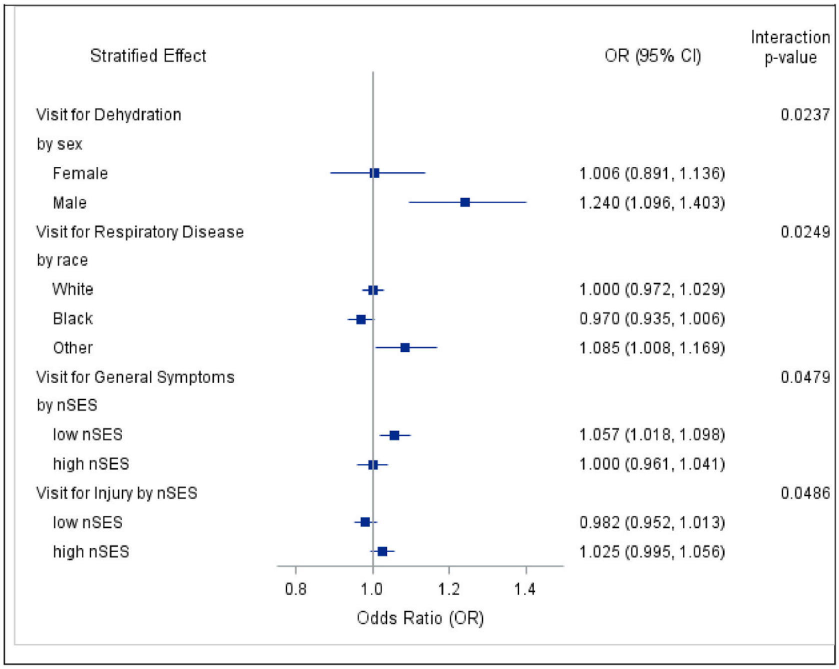

Fig. 3. Forest Plot of stratified estimates of the association between extreme heat exposure and visits for dehydration by sex, visits for respiratory disease by race, visits for general symptoms and for injury by nSES seen in urgent care visits, emergency department visits, and inpatient hospitalizations.

3.2.2. Sex (Fig. 3)

In terms of sex, male patients who were exposed to extreme heat exposure had 24 % increased odds of visits for dehydration (stratified OR [95 % CI]: 1.240 [1.096,1.403]), but female patients did not (p-value for interaction = 0.0237). No other sex differences were found for any morbidity.

3.2.3. Race (Fig. 3)

There was a differential effect of extreme heat exposure on visits for respiratory illnesses based on race (p-value for interaction = 0.0249). Among white and black pediatric patients, extreme heat exposure was unrelated to visits for respiratory illnesses. However, among patients of other races, extreme heat exposure had slightly elevated odds of visits for respiratory conditions (stratified OR [95 % CI]: 1.085 [1.008,1.169]).

3.2.4. nSES (Fig. 3)

There were differential effects by nSES for the relationship of extreme heat exposure on general symptoms (p-value for interaction = 0.0479) and injury (p-value for interaction = 0.0486). Among low but not high nSES, extreme heat exposure was associated with 6 % higher odds of visits for general symptoms (OR [95%CI]: 1.057 [1.018, 1.098]). Conversely, although marginally non-significant, among high nSES but not low nSES there was a trend for a positive relationship of extreme heat exposure on visits for injury (OR [95%CI]: 1.025 [0.995, 1.056]).

4. Discussion

Our study examined the associations between extreme heat exposure and discharge diagnoses among pediatric patients, revealing a complex relationship that varies across different discharge diagnoses and demographic groups. Our results provide valuable insights into the limited research on children's vulnerability to heat [5,7], offering caregivers and communities guidance for developing prevention strategies to protect children from the effects of extreme heat.

4.1. Discharge diagnoses

Our study results reveal that extreme heat exposure correlates with an increased incidence of discharge diagnoses for dehydration, general symptoms, heat-related illnesses, and infections in pediatric patients. Our findings broadly align with previous research in New York [29,30] and international research [31–33], indicating that elevated temperature is linked to an increased risk of emergency department visits and hospitalizations among children.

Our results are further supported by recent reviews, such as those by Oerther and Bultas [7] and Uibel et al. [5], which also report associations between extreme heat and pediatric diagnoses of dehydration, heat-related illnesses, and infections. Also, a review by Sun et al. [6] highlights that extreme heat adversely affects adults, indicating a broad vulnerability to heat exposure across age groups. These findings emphasize the need for increased vigilance and preventive measures to protect vulnerable populations during extreme heat events.

Additionally, we did not observe a significant rise in discharge diagnoses for respiratory diseases during periods of extreme heat. Our results align with several studies that have reported a negative correlation between discharge diagnoses for respiratory diseases during extreme heat exposure [29,30,32]. For instance, van Loenhout et al. [32] analyzed data from the Netherlands (2002–2007) and found that heat increased hospitalization risks for heat-related illnesses in children under 15, though no rise was noted for respiratory diseases. Similarly, Sheffield et al. [29] observed that in New York City, children aged 0–4 years had higher emergency department visits for heat-related illnesses and infections during summer but not for respiratory diseases.

Conversely, several international studies have documented an increase in pediatric respiratory admissions associated with high temperatures [34,35]. Also, a recent review by Oerther and Bultas [7] highlighted that prior research in the United States consistently shows a significant rise in pediatric discharge diagnoses for respiratory diseases during episodes of extreme heat exposure. For instance, research conducted in California found that elevated ambient temperatures during hot weather were linked to higher admission rates for respiratory diseases in young children [36].

The increase in respiratory diseases associated with extreme heat may be linked to higher levels of indoor allergens and ozone during hot weather in various parts of the United States and the world, which can irritate the underdeveloped respiratory systems of children [37]. Additionally, outdoor air pollution and simultaneous exposures may further contribute to the heightened risk of respiratory diseases during extreme heat in these regions [37]. Furthermore, the geographical area of our study might lack some common factors that contribute to respiratory issues, such as elevated allergen levels or urban heat islands, although large cities like St. Louis, included in the study area, are likely to experience urban heat island effects [9]. Monitoring these trends over a longer period and across different regions is essential for understanding broader patterns and potential delayed impacts on respiratory health.

4.2. Demographics

We also hypothesized that the impact of extreme heat exposure on healthcare discharge diagnoses would vary by demographic factors such as age, sex, race, and nSES. Our results from the all-cause cohort indicate that if we focus on a more disadvantaged population, we might observe an even higher level of risk. Additionally, the stratified analyses provided mixed results.

4.2.1. Age-specific associations

Our study demonstrates that age influences how pediatric patients respond to extreme heat exposure. Specifically, we found that infants under one year old were less likely to receive healthcare discharge diagnoses for all causes during periods of extreme heat, perhaps due to less exposure. Children aged one to four were more likely to present with general symptoms, indicating this age group may be more vulnerable due to greater mobility and activity, which can lead to faster dehydration and heat-related illnesses, or that parents/guardians of younger children may be more likely to seek care for their child's general symptoms. Our findings align with our hypothesis that age modulates the impact of extreme heat on health outcomes.

In contrast to our results, a study by Teyton et al. [38] indicated that infants experienced an increased risk of emergency department visits when exposed to all definitions of heat. The study found that the 99th percentile of minimum temperatures over a three-day period was associated with the highest adjusted odds ratio (AOR: 1.14; 95 % CI: 1.05–1.23) for the total population. Term infants were more affected by certain heat waves compared to preterm infants. Additionally, the analysis identified effect modification, such as variations based on maternal education level.

This discrepancy with our results underscores a gap in understanding the impact of extreme heat on infants. Our research suggests a decreased likelihood of healthcare discharge diagnoses during extreme heat events. This finding highlights the need for further investigation to determine whether this trend reflects genuinely lower exposure or if it arises from caregivers not recognizing symptoms. Additionally, exploring why infants are affected differently compared to older children could improve our understanding of developmental vulnerabilities to heat, providing valuable insights into pediatric environmental health.

4.2.2. Sex disparities

Our findings emphasize the potential impact of sex on the health effects of extreme heat exposure, especially regarding dehydration. We observed that male patients are more likely to seek healthcare for dehydration following extreme heat exposure, while female patients are not. The results suggest a sex-specific difference in impact, potentially influenced by physiological variations, behavioral patterns, or differences in exposure levels. These findings align with Belval et al. [39], who also identified that males and younger individuals face a higher risk of exertional heat stroke under similar environmental conditions. This consistency reinforces our hypothesis that sex is a significant factor in determining responses to heat-related events.

Moreover, the increased susceptibility among males may be attributed to behavioral factors, such as participating in more physically demanding activities during hot conditions. Overall, our findings offer important insights into the sex-specific impacts of extreme heat exposure on health, especially regarding dehydration-related healthcare outcomes.

4.2.3. Race disparities

Our findings indicate that individuals identified as "other" race had a slightly higher incidence of respiratory condition diagnoses upon discharge, with no significant differences observed in Black or White patients. This offers limited support for our hypothesis that race influences the health impacts of extreme heat exposure, suggesting that these impacts might not be uniform across all conditions or racial groups.

Contrary to our findings, Bernstein et al. [40] reported that minority racial group children and those with public insurance had a stronger association with emergency department visits due to heat compared to White children and those with private insurance. No consistent pattern emerged based on race or insurance status in their stratified analysis. However, minority children had higher emergency department visitation rates for specific issues such as bacterial enteritis, endocrine, nutritional, and metabolic diseases, mental disorders, and injuries. Bernstein et al.'s [40] results align with previous studies highlighting disparities in emergency department utilization among low-income and minority children in the U.S [41,42]. The combined results from our study and previous research emphasize the complex relationship between race, environmental factors, and health outcomes. They highlight the influence of racial demographics and local climate conditions, underscoring the need for targeted public health interventions to address these disparities.

4.2.4. nSES impact

The impact of extreme heat events on healthcare discharge diagnoses for general symptoms and injuries varied depending on the nSES. In low nSES areas, there were higher odds of healthcare discharge diagnoses for general symptoms during extreme heat exposure. Conversely, in high nSES areas, there was a marginally positive association with healthcare discharge diagnoses for injuries. Our analysis does not account for potential confounding factors, such as the association between heatwaves and higher concentrations of air pollutants (e.g., particulate matter, ozone, and aeroallergens), which can impact health. Our study results align with our hypothesis that socioeconomic factors can modulate the health effects of extreme heat.

A review by Schapiro et al. [43] on the impact of extreme heat on children's health underscores that the adverse effects are experienced inequitably, with children from lower socioeconomic status families bearing a greater burden. This heightened vulnerability is often exacerbated by inequities in housing and community infrastructure, such as limited access to air conditioning and quality healthcare, as highlighted by the Early Childhood Scientific Council on Equity and the Environment [44]. In low socioeconomic status communities, factors like inadequate healthcare access, poor living conditions, and environmental stressors contribute to a higher prevalence of chronic health conditions among children [21]. During extreme heat events, these vulnerabilities can lead to worsened health outcomes, as children may struggle to cope with the additional stress of heat exposure due to existing health issues or insufficient resources to mitigate heat effects [21,43,45,46].

4.3. Knowledge gaps

It is essential to consider future research that explores effective strategies for addressing health vulnerabilities related to extreme heat exposure and guiding the development of public health strategies to protect pediatric patients. Conducting longitudinal studies would track trends, explore the impacts of behaviors and the local environment, understand the vulnerability of demographic groups, and study the effectiveness of heat mitigation strategies across different groups, which could help plan more effective public health interventions. Collecting detailed data on symptoms and conditions leading to pediatric healthcare visits during extreme heat exposure would aid in understanding the health impacts of heat exposure. It also underscores the necessity of customizing climate adaptation strategies for different communities, as one-size-fits-all approaches may not be effective.

4.4. Implications

Our study results highlight the heightened vulnerability of children, particularly those aged 1–4, to the adverse effects of extreme heat. Our study results also emphasizes that male children are more susceptible to dehydration, necessitating vigilant care from caregivers during heatwaves. Our findings underscore the importance of culturally and demographically tailored health communication strategies to effectively address the diverse needs of different communities. By doing so, caregivers can be better equipped to recognize symptoms of heat-related illnesses and implement preventive measures to protect children.

To address these challenges, health promotion efforts in communities and preschools should focus on education and awareness about the dangers of heat for children 1–4 years old. Programs must emphasize recognizing heat-related illness symptoms and implementing preventive measures, like ensuring access to water and shaded areas. By tailoring these initiatives to meet the diverse needs of caregivers from different socioeconomic and racial backgrounds, communities can ensure that all children are protected and properly cared for during extreme heat events.

Finally, collaboration between local and state governments, schools, researchers, emergency services, and meteorologists is essential for establishing effective heat-health warning systems. By working together, these stakeholders can identify threshold temperatures that trigger warnings, allowing communities to take timely protective actions. Integrating real-time weather data with healthcare data on morbidity trends can enhance the accuracy and effectiveness of these systems. Additionally, governments can develop policies to allocate resources and support for the most vulnerable populations, ensuring that all children have the protection they need against the adverse effects of extreme heat.

4.5. Limitations

Our study had several limitations that need to be acknowledged to fully interpret and understand the findings. The study was conducted using data from Midwest states in the United States (Missouri, Wisconsin, Oklahoma, and Southern Illinois), which may limit the generalizability of the results to regions with different climates, socioeconomic backgrounds, and healthcare systems. Additionally, we might have missed some acute care visits since the database is limited to healthcare encounters in a single health system. Patients might visit out-of-system providers for care, depending on the local availability of SSM Health providers.

Furthermore, as a retrospective analysis of Electronic Health Records, this study is inherently limited by the accuracy and completeness of the recorded data, which may lead to misclassification. Also, while the strength of case-crossover analyses is that time-invariant individual characteristics are inherently controlled for because patients serve as their own controls, there may be some important time-varying characteristics that could influence health outcomes during extreme heat exposure, such as behavioral patterns not available in electronic health records (e.g., time spent outdoors, access to air conditioning, types of activities), potentially affecting the robustness of the associations found. In addition, the study defined extreme heat exposure based on daily temperatures greater than the 90th percentile for the month, which is a relatively broad and non-specific criterion and does not account for other critical factors like nighttime temperatures.

Moreover, the study lacks longitudinal follow-up of patients after discharge from urgent care visits, emergency department visits, and inpatient hospitalization settings, which limits the understanding of the long-term health impacts of extreme heat exposure. The analysis also might be limited by the categorizations used for demographic impacts (age, sex, race, nSES), potentially oversimplifying complex interactions.

With the present study design, extreme heat exposure may not have occurred on or just before the case day, and lag effects of exposure were not considered. Additionally, daily levels of heat exposure, air pollution, or humidity levels were not accounted for in the study.

Finally, the study may be underpowered to detect significant associations, particularly those involving less common conditions like diabetes and heat-related illnesses. Despite these limitations, the study provides valuable insights into the relationship between extreme heat exposure and pediatric discharge diagnoses across various healthcare settings.

5. Conclusion

Our study explored the relationship between extreme heat exposure and pediatric healthcare discharge diagnoses within a Midwestern healthcare network across Missouri, Wisconsin, the Oklahoma City metropolitan area, and Southern Illinois, all in the United States. We identified significant associations with dehydration, general symptoms, heat-related illnesses, and infections. The impact of extreme heat exposure differed across demographic groups, with the most vulnerable being children aged one to four years, males, and individuals from low socioeconomic status areas. Our findings highlight important opportunities for health promotion in communities and preschools. Better informing caregivers of the risks and implementing policy level initiatives may help reduce pediatric exposure to extreme heat. Future research should focus on longitudinal studies to explore these dynamics further and develop effective heat mitigation strategies to protect vulnerable pediatric populations from the adverse effects of extreme heat.

CRediT authorship contribution statement

Sarah Oerther: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Zachary Phillips:** Writing – review & editing, Formal analysis, Data curation, Conceptualization. **Zidong Zhang:** Writing – review & editing, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Joanne Salas:** Writing – review & editing, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Sarah Farabi:** Writing – review & editing, Validation, Methodology, Conceptualization. **Tamara Otey:** Writing – review & editing, Validation, Methodology, Funding acquisition, Conceptualization.

What does this paper contribute to the wider global clinical community?

- Worldwide health promotion efforts should focus on educating communities and preschools about heat-related dangers for young children, emphasizing symptom recognition and preventive measures.
- The varying impact of extreme heat exposure suggests a need for culturally and demographically tailored health communication and intervention strategies.
- Collaboration among local and state governments, schools, researchers, emergency services, and meteorologists is crucial for developing effective heat-health warning systems and policies to support vulnerable pediatric populations, integrating real-time data to enhance system accuracy.

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials.

Ethics declaration

Review and/or approval by an ethics committee as well as informed consent was not required for this study because this article did not use individual human subjects. All data used are publicly available.

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Declaration of competing interest

The authors declare the following financial interests/per;sonal relationships which may be considered as potential competing interests: Sarah Oerther reports financial support was provided by the National Institute of Environmental Health Sciences of the National Institutes. Sarah Oerther reports financial support was provided by Just-In-Time (JIT) Core Usage Funding Program (Washington University). Sarah Oerther reports financial support was provided by Spark Grant (Saint Louis University). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2025.e42129.

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