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Extreme heat and risk of pediatric emergency department visits: a time-stratified time-series analysis

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BACKGROUND: Children are vulnerable to heat, yet evidence on heat-related pediatric emergency department (ED) use in Germany remains limited. We quantified the acute short-term effects of extreme heat exposure on ED visits among children aged 0–18 years in Baden-Württemberg, Germany.
METHODOLOGY: We assessed short-term effects of extreme heat on ED visits among children aged 0-18 years, including perinatal conditions in infants born at or after 22 weeks´ gestation, in Baden-Württemberg, Germany using 2.83 million records from (2014–2022). A time-stratified quasi-Poisson design with distributed lag non-linear model (lag 0–5 days) was applied, adjusting for air quality, spatiotemporal factors, and COVID-19 hospitalizations.
RESULTS: Higher temperatures increased ED visits risk, strongest within 0–2 days. Cumulative relative risks increased by 4.2% (95% CI 3.7–4.8), 7.1% (6.1–8.1), and 9.6% (8.2–11.1) at the 95th, 99th, and 99.9th temperature percentiles, respectively. Heat-sensitive diagnoses included heat-related illnesses (+63%, 51–76), perinatal conditions (+57%, 26–92), and otitis media and externa (+25%, 16–33). Children < 5 years had higher ED visit rates share on hot days (RR 1.036, 1.02–1.05).
CONCLUSION: Heat exposure increases pediatric ED use, highlighting the need of child-specific thresholds and targeted preparedness strategies.

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IMPACT:

- Extreme heat increases pediatric emergency visits, especially among infants and young children.
- By combining high resolution meteorological data with a large pediatric dataset and advanced time stratified modeling, the study provides detailed evidence on short-term effects of heat and identifies specific heat sensitive diagnoses.
- The study highlights rapid, lagged effects of heat and suggests pediatric specific temperature thresholds that may better capture risk than current heat warning thresholds.
- The findings support improving preparedness in pediatric emergency care and inform adaptations to heat warning-systems to better cater for child populations.

INTRODUCTION

Rising temperatures and more frequent extreme heat events pose increasing risks to children's health.[1] While health impacts of extreme heat have been widely studied in general populations, less attention has been given on how these trends affect the pediatric population. Children are increasingly exposed to elevated ambient temperatures, leading to an increased occurrence of heat-related illnesses, infectious diseases, respiratory and cardiovascular diseases, and mental health challenges.[2] Infants and young children are especially susceptible because their

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thermoregulatory systems are immature, their ability to sweat is limited, and their high body surface area relative to body mass increases metabolic demands for cooling.[3,4] Their inability to recognize symptoms of heat stress or seek relief independently makes them heavily reliant on caregivers, while higher activity levels further heighten their susceptibility of heat stress.[4] So far, most existing studies have been conducted in North America and Asia, with little emphasis on the pediatric population in Europe, particularly in Germany.[5,6]

Germany has experienced a steady rise in temperatures, and heatwaves have become more frequent and severe in recent years. Urban areas, particularly the Upper Rhine and Neckar regions, experience intensified heat stress due to the "urban heat island effect".[7] Recent mortality analysis from Germany has shown that extreme heat is associated with a significant excess mortality of approximately 8700 heat-related deaths in 2018, 6900 in 2019, and 9100 (95% CI: [7300; 10,700]) in 2022.[8] Although Germany has committed to achieving net-zero greenhouse gas emissions by 2045 and has outlined corresponding plans in the National Climate Protection Act, adaptation measures specifically targeting children are still lagging behind.[9] A recent policy analysis across 160 countries found that most national adaptation plans, including Germany's, largely neglect child-specific health needs.[10]

Current adaptation actions in Germany are limited to small-scale interventions such as opening public cooling centers, while more comprehensive plans, such as prioritizing heat-adaptive schools or creating early warning systems specifically for children have not yet been implemented.[11] Without timely improvements in both policy and practice, these gaps are likely to exacerbate the health risks among children and increase the burden on pediatric emergency services.

Based on these research gaps, this study aims to quantify the impact of extreme heat on pediatric emergency healthcare utilization in Germany by analyzing the association between heat exposure and all-cause and cause-specific emergency department (ED) visits, defined as both in-patient and out-patient emergency visits, among children aged 0–18 years in Baden-Württemberg. The objective was to identify heat-sensitive pediatric conditions, characterize high-risk subgroups, and examine differences between ED and OPD visits, to inform child-centered, evidence-based adaptation strategies for pediatric healthcare and climate resilience.

METHODS

Study design

Using ICD-10–coded in-patient and out-patient emergency department visits data spanning 2014–2022 from the health insurance company Allgemeine Ortskrankenkasse Baden-Württemberg (AOK-BW), the third-largest statutory health insurance provider in Germany, along with meteorological data from the ERA5-Land reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), and air-pollutant concentrations from the Copernicus Atmosphere Monitoring Service (CAMS) European reanalysis, we applied a time-stratified quasi-Poisson time-series analysis design, analogous to case-crossover methods, with temperature lags (0–5 days) to assess the acute effects of extreme heat on child ED visits, defined as the 95th, 99th, and 99.9th percentiles of state-specific daily mean daytime temperature. The time-stratified design compares daily ED visit counts per postal code to ED visit counts on control days matched within the same time strata, enabling estimation of the relative change in ED visit rates (incidence rate ratios) associated with near-surface air temperature. Our time strata were defined by year and calendar month, and models included a day-of-week factor and a continuous time index to control for temporal trends.

This study was conducted in Baden-Württemberg (BW), located in the southwest corner of Germany. In 2022, the population was 11.2 million, accounting for 13.5% of the total population of Germany.[12] The climate in BW varies from oceanic in the west to humid continental in the east.[13] Notably, the Upper Rhine Valley, which runs along the western side of the state, is among the hottest regions in the nation, as measured by the number of days per year with temperatures above 30 °C.[7]

Exposures

Meteorological data, including daytime mean, minimum, and maximum air temperature at 2 meters above ground, and relative humidity, were obtained together with air quality data comprising daily mean concentrations of fine particular matter (PM_{10} and $PM_{2.5}$), nitrogen dioxide (NO_2), and ground level ozone (O_3). Daytime air temperature specifically refers to the mean, minimum, and maximum temperature from 8 am to 8 pm. Relative humidity was derived from dew point temperature at 2 m above ground (°C) applying an empirical formula.[14] Meteorological variables were derived using ERA5-Land, a reanalysis dataset generated by running a land surface model forced by ERA5 meteorological variables, which are produced through the assimilation of a wide range of in situ measurements and satellite observations into a numerical weather prediction model.[15] Air pollutant concentrations (PM_{10}, $PM_{2.5}$, NO_2, and O_3) in ambient air were derived from the CAMS European Air Quality Reanalysis,[16] which provides gridded concentrations of major atmospheric pollutants based on a regional chemistry–transport model ensemble comprising eleven models constrained by emissions inventories and assimilated observations.

All environmental variables were originally available at an hourly temporal resolution and a native spatial resolution of 0.1° x 0.1°. Daily exposure metrics at the postal code level were derived by resampling hourly gridded data to a finer grid using bilinear interpolation, followed by spatial aggregation to postal code areas and temporal aggregation to daily aggregates. As this analysis overlaps with the COVID-19 pandemic, the 7-day incidence rate of hospitalized COVID-19 cases (by case reporting date) per 100,000 persons in Baden-Württemberg was included as covariate in the analysis, with dates prior to the pandemic coded with incidence rate of zero. COVID-19 hospitalizations were obtained from the Robert Koch Institute (RKI)[17] official statistics, spanning March 1st, 2020 to December 31st 2022. Hospitalization rates for all ages were chosen as the child hospitalization rates did not fully overlap with our child subgroup, as the RKI rates were for ages 0–15 compared to our child subgroup of 0–18.

Outcomes

The main outcome was in-patient and out-patient ED visits sourced from AOK health records. These records included all ED visits of children aged 0–18, including perinatal conditions in infants born at or after 22 weeks´ gestation, insured by AOK in Baden-Württemberg from 2014 to 2022. Records were anonymized by AOK and included patient age, sex, diagnosis, day of ED visit, the postal code of their home address, and the distance to the nearest hospital. For the purposes of this analysis only emergency patients were considered. As a result, ED visit counts combine both emergency admission of in-patient and out-patient cases as a single outcome variable. Diagnoses were coded using the International Classification of Disease, 10^{th} revision (ICD-10) at the three-digit level. Secondary outcomes included the distribution of ED visits across 21 disease categories covering major organ systems such as respiratory, cardiovascular, neurological, digestive, endocrine, dermatological, musculoskeletal, and genitourinary as well as heat-related illnesses, injuries, and mental and behavioral disorders.

Statistical analyses

Patient home postal code was used as a categorical covariate to control for spatial effects, as well the straight-line distance from the centroid of each postal code to the nearest hospital was included to account for spatial variation in access to care. Daily mean surface concentrations of PM_{10}, $PM_{2.5}$, O_3, and NO_2, as well as relative humidity were also included to control for potential confounding by air quality and meteorological conditions. To adjust for the impact of the COVID-19 pandemic on hospitalization, we included the 7-day incidence rate of hospitalized COVID-19 cases per 100,000 persons across all ages in Baden-Württemberg with dates prior to the pandemic coded with incident rates of zero. All covariates were modeled as linear terms with the exception of temporal and spatial factors.

To account for the acute effects of heat on ED visits among individuals 18 years old and younger, both immediately and with short delay, we employed a distributed lag non-linear model (DLNM) within a generalized linear model framework. The quasi-Poisson distribution was used in order to account for overdispersion in daily ED visit counts.[18] For the temperature cross-basis term, natural cubic splines were specified for both the temperature and lag dimensions, with three degrees of freedom each and knots placed at equally spaced quantiles of the observed temperature and lag distributions. The lag period was restricted to 0–5 days to capture acute heat-related effects on child ED visits. We tested

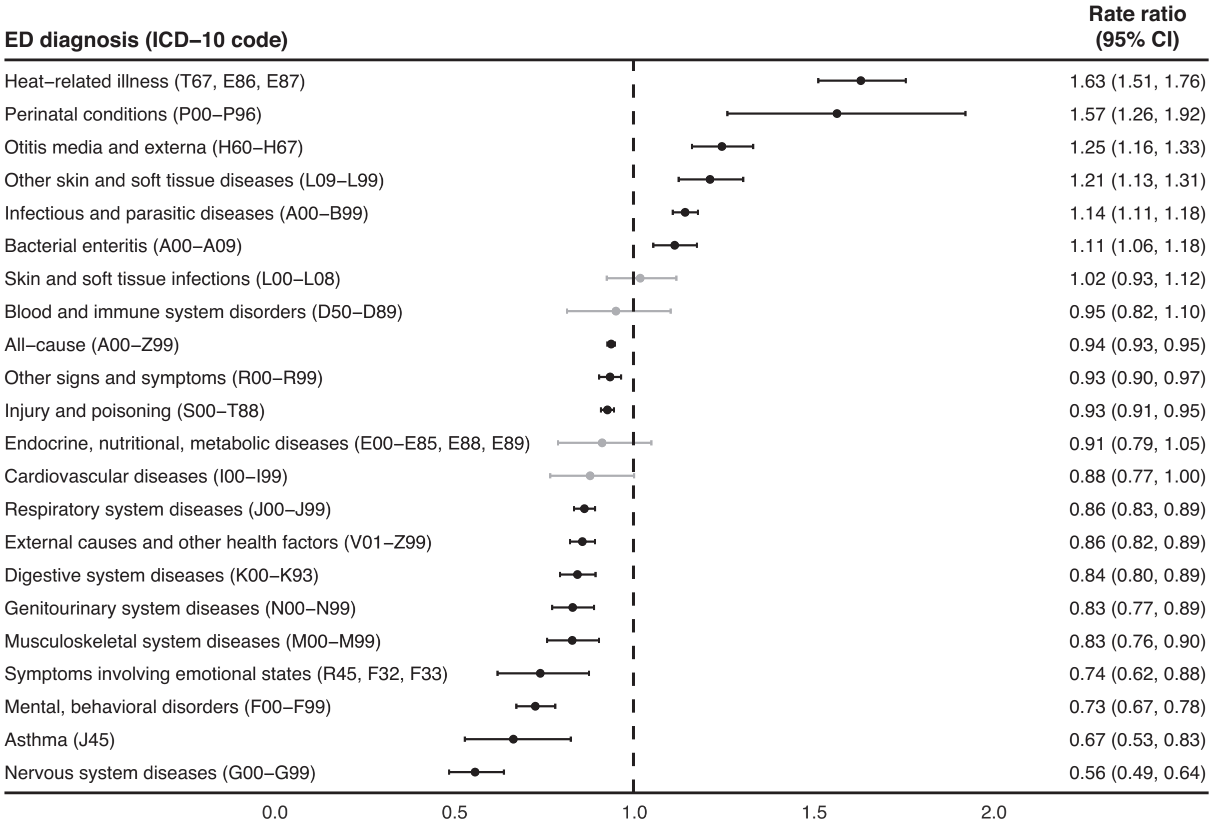

Fig. 1 ED Diagnoses on high-risk heat days (mean daytime temperature ≥26.7 °C) compared to low- to moderate-risk heat days (temperatures <26.7 °C) by disease category. High-risk heat day temperatures defined as greater than or equal to the 99th percentile.

lag periods of 0–3, 0–5, and 0–7 days as well as alternative spline flexibilities for both temperature and lag (3 and 5 degrees of freedom) in sensitivity analyses. The final model was selected using the quasi-Akaike Information Criterion (QAIC). All analyses were conducted in R version 4.4.0 with all DLNMs implemented with the dlnm package.[19]

In addition to our time-stratified analysis, we exploratorily assessed whether high-risk heat days (26.7 °C) were associated with higher diagnosis rates for specific disease categories using a Poisson exact, and whether ED visit rates varied by age using a χ^2 test, compared with low- to moderate-risk heat days (defined as days with mean daytime temperatures below 26.7 °C). Disease categories were based on previous research by Bernstein et al.[20]. The Benjamini-Hochberg method was used to correct for multiple testing. All findings reported were statistically significant at either the 95% or 99% level after correction.

RESULTS

Exploratory Analyses

Emergency department admissions. Across the study period there were 2,839,077 emergency in-patient and out-patient medical admissions in Baden-Württemberg. Among these patients, 53% were male and 47% were female and 53% were aged 5 or younger. In the warm months of May to September, the proportion of patients aged 5 or younger dropped to 47.5%. However, when comparing high-risk heat days (26.7 °C) to low- to moderate-risk heat days (all temperatures below daytime mean of 26.7 °C) from May to September, children aged 5 or younger made up a larger share of ED visits on high-risk heat days (49.1% versus 47.4%). A difference which was statistically significant (χ^2 $P < 0.0001$). This corresponds to children aged 5 or younger comprising a 3.6% higher share of ED visits on high-risk heat days (risk-ratio = 1.036, 95% CI [1.02; 1.05]), suggesting that there are small but differential effects of heat on the risk of ED visits across broad age groups.

Disease-specific diagnosis rates

We found that heat-related illnesses (T67, E86, E87) including heatstroke, sunstroke, dehydration, and electrolyte disorders were diagnosed at rates 63% (95% CI [51%; 76%]) elevated on high-risk heat days compared to low- to moderate-risk heat days. Perinatal conditions (P00-P96) were diagnosed at 57% (95% CI [26%; 92%]) higher rates, while otitis media and externa conditions (H60-H67) and skin and soft tissue diseases (L09-L99) were diagnosed at 25% (95% CI [16%; 33%]) and 21% (95% CI [13%; 31%]) higher rates on high-risk heat days, respectively. Notably diagnosis rates for asthma (J45) and respiratory diseases (J00-J99) were 33% (95% CI [17%; 47%]) and 14% (95% CI [11%; 17%]) lower on high-risk heat days, respectively. For the full Poisson exact test results see (Fig. 1).

An additional sensitivity test was also performed to assess diagnosis rates on days with temperatures exceeding the 95th percentile (mean daytime temperature ≥ 24.1 °C) compared to days with lower temperatures. These results largely consistent with the primary analysis, identifying similar diagnoses increasing and decreasing during hot weather, although with more moderate changes in estimated diagnosis rates. For the full sensitivity analysis results see the Supplementary Material (Appendix Fig. 1).

DLNM Analyses

Marginal RR. The marginal RR for each lag is presented in (Fig. 2). Across all six lag periods, Lag 0 (same day), Lag 1 (next day), and Lag 2 (two days later) had the strongest impact on expected ED visits due to heat, while Lags 3, 4, and 5 had limited to no effect. For example, on the first day of exposure (Lag 0) to 24.1 °C (95th percentile), the relative risk of an ED visit increased by 1.8% (95% CI [1.4%; 2.1%]). For Lags 1 and 2, the increases were 1.4% (95% CI [1.2%; 1.5%]) and 1.0% (95% CI [0.8%; 1.2%]), respectively. At Lag 3, three days after initial exposure, it was 0.5% (95% CI [0.3%; 0.7%]), but by lags 4, and 5, estimates were close to zero for most

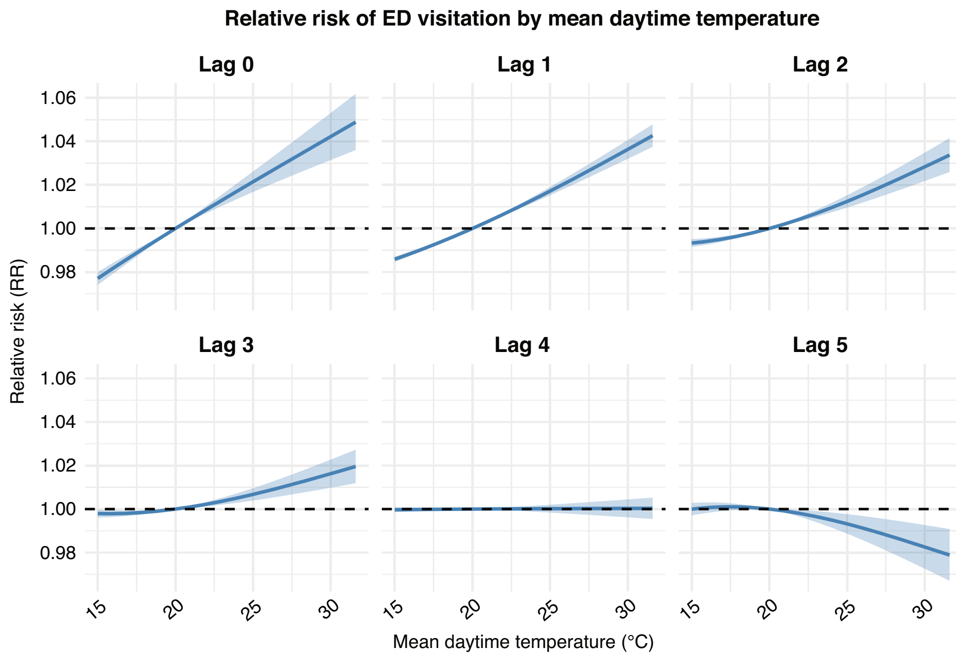

Fig. 2 Marginal relative risk curves by lag period. Each graph represents the marginal effect of mean daily air temperature on the relative risk of an ED visit in ascending order from the day of exposure (Lag 0) to 5 days after initial exposure (Lag 5).

exposures.

For the 26.7 °C (99th percentile) and 28.9 °C (99.9th percentile), the same pattern persisted with the strongest effects of heat associated with Lags 0 to 2 with limited effect by Lag 3 and no clear effects by Lags 4 and 5. Specifically, the marginal relative risk of an ED visit on Lag 0 increased by 2.9% (95% CI [2.2%; 3.5%]) and 3.8% (95% CI [2.8%; 4.7%]) for 26.7 °C and 28.9 °C, respectively. On Lag 1, the relative risk of an ED visit increased by 2.4% (95% CI [2.1%; 2.6%]) at 26.7 °C and at 28.9 °C it increased by 3.2% (95% CI [2.8%; 3.6%]). On Lag 2, the increase in relative risk was 1.8% (95% CI [1.4%; 2.2%]) and 2.5% (95% CI [1.9%; 3.0%]) for 26.7 °C and 28.9 °C. This pattern remained similar at higher temperatures, though with a longer carryover effect with the increase in relative ED visits sustaining through Lag 3 or temperatures over 30 °C. However, the increase in relative risk of an ED visit on Lag 3 was small compared to earlier lags for these temperatures. By Lags 4 and 5 the effect of temperature on visit counts had largely diminished.

Cumulative RR

Cumulative relative risk, which includes the combined effects of temperature on the relative risk of an ED visit across all lag days, increased monotonically with temperature, with an approximately linear trend from the baseline temperature of 20 °C to the maximum recorded mean daytime temperature of 31.6 °C in our dataset. At 24.1 °C, 26.7 °C, and 28.9 °C, the cumulative relative risk of an ED visit increased by 4.2% (95% CI [3.7%; 4.8%]), 7.1% (95% CI [6.1%; 8.1%]), and 9.6% (95% CI [8.2%; 11.1%]), respectively.

Impact of Heatwaves on Risk of ED Visits

To assess the impact of heatwaves on the cumulative relative risk of an ED visit, we simulated the impacts of three consecutive days of elevated temperatures followed by five days of the model's baseline mean daytime temperature of 20.0 °C. The five days of consecutive baseline temperatures are to allow for the full estimation of any lagged effects of high temperature days on the relative risk of an ED visit. This scenario was repeated for each of the three temperature thresholds 24.1 °C, 26.7 °C, and 28.9 °C corresponding to the 95th 99th and 99.9th percentiles respectively of mean daytime summer temperatures in Baden-Württemberg (Fig. 3).

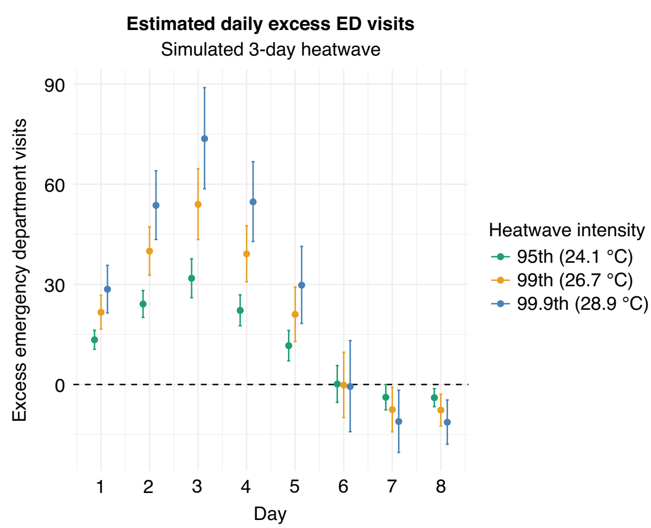

Fig. 3 Excess daily ED visits during a simulated 3-day heatwaves followed by five days of baseline temperatures (20 °C). The three colors indicate heatwave intensity, defined by mean day temperatures at the 95th (24.1 °C), 99th (26.7 °C), and 99.9th (28.9 °C) percentiles of summer temperatures in Baden-Württemberg from 2014 to 2022. Points represent daily excess ED visit estimates with the bars representing the 95% confidence intervals.

In all three scenarios, the daily ED visit rate ratio peaked on the third day of the 8-day period with daily relative increases of 4.2% (95% CI [3.4%; 5.0%]), 7.1% (95% CI [5.7%; 8.5%]), and 9.7% (95% CI [7.7%; 11.8%]), in ascending order from the 24.1 °C heatwave to the 28.9 °C heatwave. Regarding the estimated impact on ED visits, the 24.1 °C percentile heatwave would lead to an excess of 96 ED visits (95% CI [62; 130]) over the 8-day period relative to the average daily ED visit count observed in this study, while the

26.7 °C heatwave would lead to an excess of 160 ED visits (95% CI [100; 221]) and the 28.9 °C heatwave an excess of 217 ED visits (95% CI [132; 304]).

Regional patterns of heat-attributable ED visits

Across the entire study period there were an estimated 8626 excess ED visits among children insured by AOK due to heat in Baden-Württemberg. Excess ED visits were concentrated disproportionately in the western and central, northwest of the state. The top 5 districts by absolute excess ED visits were Stadtkreis Mannheim with 579 excess ED visits, Landkreis Ludwigsburg with 491, Landkreis Karlsruhe with 487, Landkreis Ortenaukreis with 445, and Landkreis Rhein-Neckar-Kreis with 415 excess ED visits. The top 5 districts by absolute excess ED visits additionally accounted for 28.1% of total excess Ed visits attributable to heat.

The fraction of ED visits attributable to heat was much more concentrated in the northwestern portion of the state, compared to absolute excess ED visits (Fig. 4). The top 5 districts by the fraction of ED visits attributable to heat were Stadtkreis Karlsruhe with 1.3% of ED visits due to heat, Stadtkreis Mannheim with 1.3%, Landkreis Karlsruhe with 1.2%, Stadtkreis Heidelberg with 1.1% and Landkreis Rhein-Neckar-Kreis with 1.1%. Notably, of the top districts by absolute excess ED visits, only Stadtkreis Mannheim and Landkreis Karlsruhe were in the top 5 districts for both absolute and relative excess ED visits.

Control variable results

Of the controls variables considered in this study, day-of-week effects, COVID-19 hospitalization rates, mean daily PM_{10}, $PM_{2.5}$, and NO_2 concentrations, as well as relative humidity were all statistically significant at the 99% level. Mean daily O_3 concentration and distance to the nearest hospital were not statistically significant.

DISCUSSION

Our current study demonstrated a clear and statistically robust association between higher ambient temperatures and increased pediatric ED visits using 2.83 million cases of children and young adults aged 0–18 years, including perinatal conditions in infants born at or after 22 weeks´ gestation, in Baden-Württemberg between 2014 and 2022. To our knowledge, this is the first study in Germany to quantify the acute effects of heat on pediatric ED visits using a distributed lag non-linear model. The highest risks were observed within 0–2 days after heat exposure, consistent with the short lag times reported in previous epidemiological studies and with known physiological responses to heat stress.[20,21] Importantly, we observed increased ED visit rates at temperatures around 24.1 °C, supporting and extending earlier evidence that clinically relevant heat effects in children occur well below commonly used heat-warning thresholds. Forward simulations showed a linear rise in ED visit rates from approximately 20 °C upwards, with risk accumulating over consecutive warm days and short-term lagged effects persisting after temperatures declined to around 20 °C. We further estimated 8,626 excess pediatric ED visits attributable to heat, with the highest burden concentrated in urban districts, consistent with increased heat exposure associated with urban island heat effects.

Infants and young children aged 5 or younger emerged as the most vulnerable subgroup, reflecting their limited thermoregulatory capacity, higher surface-area-to-mass ratio, and dependence on caregivers for hydration and environmental modification. Our cause-specific analysis identified diagnostic categories that were particularly heat sensitive. As expected, heat-related illnesses were more common on hotter days, but we also found increased risks for perinatal conditions, otitis media and externa, and skin and soft tissue infections. These findings point to heat acting not only as a direct physiological stressor but also as an immunological and systemic stressor in early life.

Our results are consistent with previous work from other high-income settings. A multicenter study in the US reported increased pediatric ED visits during hot periods, with the strongest associations at lag 0 and elevated risks persisting for 2–3 days, mirroring the short-term patterns we observed. Consistent with our exposure–response relationship, that study also demonstrated a near-linear increase in all-cause pediatric ED visits across warm-season temperatures ranging from approximately 18 °C to 40 °C (corresponding to the 95th percentile in their regions). A study from southwestern Ontario, Canada, where 33 °C approximated the 99th percentile, reported delayed peaks in pediatric ED visits 2–5 days after heat exposure.[21] Studies from the USA, Canada, and South Korea have repeatedly identified infants and young children as being at highest risk, with increases in heat-related illness, infectious diseases, and otitis media and externa during hot periods.[20–22] The convergence of findings across diverse climatic contexts underscores shared physiological and clinical pathways through which heat affects children.

At the same time, our analysis offers heat-specific insights relevant to temperate European settings. In the German state of Baden-Württemberg, we found that the rate of pediatric ED visits increased at temperatures as low as 24.1 °C, corresponding to the 95th percentile of the warm-season temperature distribution. These temperature thresholds are substantially lower than those reported in North American studies,[20] indicating that pediatric heat–health relationships cannot be directly transferred across regions without accounting for previous exposures to warm temperature extremes, local behavioral and infrastructural differences such as access to air conditioning and healthcare, as well as differences in local climatic distributions, including in temperature ranges, humidity, frequency and duration of heatwaves. Our findings reinforce the need for identifying country- and region-specific thresholds for deploying alerts through early warning systems and heat-health analyses. The prominence of perinatal conditions among heat-sensitive diagnoses, a category that has received relatively little attention, further underscores fetal and neonatal susceptibility and the need for more granular investigation of specific perinatal outcomes.

These findings have several implications for clinical practice and health system planning. First, the observed increase in ED visits at temperatures below official heatwave thresholds suggests that

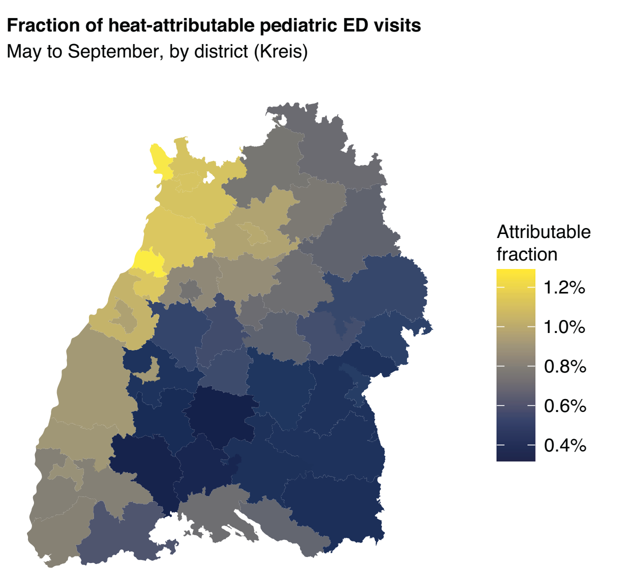

Fig. 4 Fraction of excess heat-attributable ED visits by district from May to September, 2014–2022. Brighter shades of yellow correspond to higher excess relative ED visits, while deeper shades of blue correspond to lower excess ED visits.

clinicians should consider heat as a contributing factor even on days not classified as heatwave days. Second, the concentration of risk within 0–2 days after exposure highlights heat as an acute exacerbating factor and underscores the need for heightened vigilance following warm days, especially for infants and young children and those with pre-existing conditions. In Germany, heatwave alerts issued by the national meteorological service are typically based on adult-focused thresholds, often between 32 °C and 38 °C.[11] As a result, substantial pediatric heat-related morbidity may arise without triggering formal warnings for clinicians or caregivers.[23]

The mismatch between adult-based alert thresholds and child heat vulnerability highlights the need to adapt early warning systems to incorporate age-dependent physiological thresholds. Locally derived pediatric exposure–response functions, such as those presented in our findings, could be integrated into existing early warning systems to trigger earlier or child-specific alerts. This would allow timely dissemination of information to healthcare workers, caregivers, schools, and childcare facilities, and promote adaptive measures such as increasing access to cool environments, intensifying hydration, and moderating physical activity during warm periods.

Experience from other countries illustrates how hospitals can proactively prepare for heat-related surges. In Australia, EDs have formal heatwave preparedness plans that use meteorological forecasts to activate surge protocols, mobilize staff, and adjust triage procedures to identify and manage high-risk patients.[24] In Canada and France, facility-level guidance recommends advance preparation and rapid implementation of cooling and hydration strategies in anticipation of increased cases of dehydration, heat-related illness, and febrile conditions.[25,26] In France, the ORSAN emergency response framework provides a structured model for hospital preparedness during heat events, including reallocation of staff and equipment, anticipatory capacity planning, and coordinated case reporting across hospitals.[25] Drawing on such models, pediatric EDs could incorporate brief assessments of recent heat exposure, hydration status, and physical activity into triage, and prioritize infants and young children or those with chronic conditions when heat-sensitive symptoms are present.

Improving recognition and classification of heat-related conditions is also in need of further attention. Many heat-related clinical presentations are likely to be underdiagnosed or misclassified, as has been documented in Germany via an active registry.[23] Strengthening training for healthcare staff on early signs of heat-related illness and heat-exacerbated conditions, and developing clearer clinical criteria, would improve diagnostic accuracy and help capture more accurate morbidity patterns in pediatric populations. This, in turn, would support more robust surveillance and evaluation of heat adaptation measures.

The need for pediatric-specific early warning systems is further underscored by lessons from other public health emergencies. During the COVID-19 pandemic, many countries rapidly expanded intensive care capacity and mobilized and retrained staff in response to emerging evidence of risk.[27] Following the 2019–20 bushfires in Australia, public health agencies implemented near real-time air quality monitoring, coupled with targeted advice for at-risk groups, including children and people with asthma, and guidance for schools and childcare centers.[28] These examples demonstrate that context-specific operational frameworks can be feasibly integrated into health system planning and rapidly adapted when clear risk thresholds and communication pathways are in place.

A key strength of our study is its methodological approach. The time-stratified design with DLNMs allowed us to control for seasonality, long-term trends, non-linear and lagged effects of temperature, and time-invariant population characteristics within postal codes. Precise spatial and temporal alignment of exposure was achieved using long-term ERA5 Land and CAMS reanalysis data, linked to nearly a decade of AOK pediatric ED visit records, comprising a large and regionally representative cohort of 2.83 million cases. Adjustment for COVID-19 hospitalizations helped to account for pandemic-related disruptions in healthcare utilization. Our analytical framework is fully replicable: routinely collected hospitalization data and publicly available meteorological reanalysis can be used in other regions to generate pediatric heat thresholds and risk curves. Pediatric EDs could also combine local weather forecasts with such curves to inform surge protocols when child-specific thresholds are exceeded.

This study also has limitations. First, we lacked information on effect modifiers and confounders such as housing conditions, indoor temperatures, access to cooling, and behavioral adaptations, which could influence both exposure and vulnerability. Second, we captured only acute events resulting in ED visits and therefore may underestimate the total burden of heat on children's health, including milder cases managed in primary care or at home. Third, solar exposure and wind speed influence morbidity during heat, yet those variables were not considered in this study. Additionally, the environmental data adopted has a native hourly temporal resolution, which allows the isolation of daytime temperature. However, the native spatial resolution, although bilinearly resampled as recommended by Stroh et al., may fail to capture localized temperature variability, resulting in a smoothing effect.[29] For instance, in highly urbanized areas, the urban heat island (UHI) effect or intra-urban heat variability may not be adequately represented.[30] Finally, while we examined broad ICD-10 groups, some categories, particularly perinatal diagnoses, are heterogeneous. Future work should disaggregate cause-specific pediatric ED visits by narrower diagnostic codes and age groups to clarify age-dependent physiological pathways and refine identification of heat-sensitive conditions. In particular, more detailed analyses of perinatal diagnoses are needed to determine which specific fetal and neonatal conditions are most sensitive to heat.

DATA AVAILABILITY

The anonymized AOK emergency department visit data, derived ERA5 Land meteorological data, and aggregated air pollutant concentrations from the CAMS air quality re-analyses used in this study are available from the corresponding author upon reasonable request and subject to approval from the respective data providers and completion of data-use agreements. Aggregated summary data and analysis code can be shared to support reproducibility.

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AUTHOR CONTRIBUTIONS
C.H. and K.E.Z. led the conceptualization of the study. Data acquisition and curation were coordinated by S.D. and M.B., including preparation and management of the anonymized AOK health records. ERA5 meteorological data were provided and technically supported by DLR co-authors (L.G., T.E., J.R.). Formal statistical analyses and model development were carried out by C.H., A.D., J.R., and A.B., who also contributed to the interpretation of results. Methodological development, including exposure assessment and sensitivity analyses, was jointly undertaken by C.H., K.E.Z., and A.D. Project funding was secured by K.E.Z. and T.B. Project administration and coordination with institutional partners were overseen by K.E.Z. and C.W.C. The original draft of the manuscript was prepared by C.H., D.W., C.W.C., and K.E.Z., as well as I.K. All authors contributed to reviewing and editing the manuscript for intellectual content. All authors reviewed and approved the final manuscript.

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ETHICAL APPROVAL AND CONSENT TO PARTICIPATE
The analysis utilized anonymized data on pediatric ED visits. All data were obtained from AOK and contained no personal identifiers. As no individual-level or identifiable patient data were used, no additional ethics approval was required in accordance with institutional ethical guidelines. Data handling and storage followed established data protection and privacy standards of the Heidelberg Institute of Global Health and University Hospital Heidelberg, ensuring compliance with GDPR and relevant institutional policies.

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