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Increased hospital admissions associated with extreme-heat exposure in King County, Washington, 1990-2010

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Abstract

Increased morbidity and mortality have been associated with extreme heat events, particularly in temperate climates. Few epidemiologic studies have considered the impact of extreme heat events on hospitalization rates in the Pacific Northwest region. This study quantifies the historical (May to September 1990-2010) heat-morbidity relationship in the most populous Pacific Northwest County -King County, Washington. A relative risk (RR) analysis was used to explore the association between heat and all non-traumatic hospitalizations on 99th percentile heat days, while a time series analysis using a piece-wise linear model approximation was used to estimate the effect that heat's intensity has on hospitalizations, adjusted for temporal trends and day of the week.

A non-statistically significant 2% [95% CI: 1.02 (0.98, 1.05)] increase in hospitalization risk, on a heat day versus a non-heat day, was noted for all-ages, all non-traumatic causes. When considering the effect heat intensity has on admissions, we found a statistically significant 1.59% (95% CI: 0.9%, 2.29%) increase in admissions per degree increase in humidex above 37.4 °C. Admissions stratified by cause and age produced statistically significant results with both relative risk and time series analyses for nephritis and nephrotic syndromes, acute renal failure and natural heat exposure hospitalizations. This study demonstrates that heat, expressed as humidex, is associated with increased hospital admissions. When stratified by age and cause of admission, the non-elderly (less than 85) age groups experience significant risk for: nephritis and nephrotic syndromes, acute renal failure, natural heat exposure, COPD and asthma hospitalizations.

Keywords

Climate change; morbidity; humidex; Pacific Northwest; extreme heat

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Introduction

Health-related impacts associated with extreme-heat events are of growing concern given the predicted increase in both frequency and duration of these events as a result of climate change (1). Numerous studies indicate that higher temperatures, or other indices of the physiological effect of heat and humidity, are associated with increased mortality (2-8). Research focused on hospitalization and emergency room visits has also found an increased risk associated with increasing temperatures (9-13). Studies conducted in the United States have shown an increased risk of hospitalization for diverse conditions such as heat stroke or heat exhaustion (12), acute renal failure (14), diabetes (15), respiratory (16), and cardiovascular diseases (17, 18).

Intensity and duration of heat events have been found to modify heat's effect on mortality (4, 8) and morbidity (14). Socio-demographic factors found to influence mortality and morbidity risks include social isolation (19, 3), socio-economic status (20, 19), and ethnicity and educational status (21, 14). Additionally, access to air conditioning has been found to decrease mortality (3, 22) and morbidity (15) risks. Literature suggests that these risk-modifying factors vary across different climatic regions. As average temperatures and the frequency of extreme-heat events are predicted to increase with climate change, understanding the regional heat-morbidity relationship becomes increasingly important for directing adaptation-related policy decisions.

This study investigated the relationship between heat and morbidity in the Pacific Northwest's most populous county - King County, Washington (23). We first used a Poisson, relative risk (RR) model to explore age-adjusted causes of unplanned hospital admissions. Specific causes of admission were selected *a priori* through the literature (7, 24, 25) or that were specifically requested by the local health jurisdiction. A second analysis, using a time series model, investigated heat intensity effects on morbidity. Specifically, we quantified the percentage increase in hospital admissions associated with a one-degree increase in humidex for the same list of causes-of-admission, age adjusted. Using a time series model allowed us to investigate potential effect modification from individual-level characteristics, as well as additional influences from heat including cool-down, duration, lag, and synoptic weather type effects. Lastly, we were able to examine length-of-hospital stay and admission costs. To our knowledge, no other study has looked at such a comprehensive list of morbidity categories in the Pacific Northwest, using two methods of analyses.

Methods

Hospital admissions and population data

King County hospital discharge data for all non-traumatic illnesses and external injury due to heat causes, 1990 to 2010, were obtained from the Comprehensive Hospital Abstract Reporting System (CHARS) maintained by the Washington State Department of Health. Human subjects approval was obtained from the Washington State Department of Health and Human Services Institutional Review Board. Only admissions during the summer months of May through September were analyzed. Colder months were excluded to minimize potential confounding by infectious diseases typically seen during these months. There are 153 days per constrained calendar year, a total of 3,213 days for the entire study period. In addition, this study only included those visits categorized as “emergency” (requiring immediate medical intervention) and “urgent” (requiring immediate attention), by the Washington Department of Health (26). “Elective” hospitalizations were excluded from this analysis. A total of 1,384,251 non-traumatic hospital admissions occurred during the warmer months from 1990 to 2010; 54% were unplanned. Admissions were coded using the International Classification of Diseases, Clinical Modification (ICD-9-CM) codes.

This study looked at all non-traumatic, unplanned causes of hospitalizations (ICD-9 001-799). We also investigated select subsets of non-traumatic, unplanned hospitalizations including: diabetes, circulatory, cardiovascular, ischemic, cerebrovascular, respiratory, chronic obstructive pulmonary disease (COPD), asthma, nephritis and nephrotic, acute renal failure, mental disorders, and natural heat exposure (including dehydration). Table 1 lists the specific ICD-9-CM codes used in this study.

A priori we anticipated that several individual-level characteristics may identify populations vulnerable to heat-related hospitalizations: age, gender, and socio-economic status. Furthermore, we anticipated a difference in heat-related hospitalizations by admission source (emergency room referral or non-ER referral), and admission type (emergency or urgent). Population data, by age groups (0-4, 5-14, 15-44, 45-64, 65-84, 85+) were obtained from the Washington State Office of Financial Management (OFM) (27).

Meteorology data

This study used a gridded (1/16° resolution) meteorological data set produced by the University of Washington’s Climate Impacts Group (28). Meteorological values were derived by combining the most current knowledge on regional, spatial climatic patterns with land-surface meteorological observations. Each grid cell’s center point contains daily max/min temperature, precipitation and relative humidity values for the study’s timeframe. Spatial climatic patterns were determined by the Parameter-Elevation Relationships on Independent Slopes Model (PRISM), developed and updated by Oregon State University (29), while the meteorological observations originate from the Global Historical Climate Network-Daily (GHCN), operated by the National Oceanic and Atmospheric Administration. The county-wide daily maximum temperature and average relative humidity values were used to construct our exposure metric, humidex.

Exposure assessment

As with our previous heat-mortality studies (7, 24, 30), we used humidex as the measure of exposure. Humidex is an apparent temperature index that measures the combined effects of temperature and humidity on the human body (31). An average daily maximum humidex was computed over all grid center points located in King County. Exposure to heat was estimated as the average maximum county-wide humidex value for each day within the study’s time frame.

Humidex is defined by the following formula and is expressed in units of °C:

$$\boldsymbol{Humidex}=\boldsymbol{T}+\left(\frac{5}{9}\right)\cdot(\nu-\mathbf{10}),\quad \textbf{where}\quad \nu=\left(\mathbf{6.112}\cdot\mathbf{10}^{\left[\frac{\mathbf{7.5T}}{\mathbf{237.7+T}}\right]}\right)\cdot\frac{H}{100} \qquad (1)$$

where T is the air temperature (degrees Celsius), H is the average relative humidity (%), and v is the vapor pressure (kPa) (32). In this study, the term "humidex" refers to the "county-wide average daily maximum humidex".

Association between humidex and morbidity

Relative risk analysis—A heat day was defined as a day in which the average humidex exceeds the model-derived threshold. In this analysis, we tested the 99th, 95th and 90th percentile models and chose the model that gave the best fit to the data (with a maximum likelihood). The following Poisson regression model was used:

$$\boldsymbol{E}\left(\boldsymbol{Y_j}\right)=\boldsymbol{P_j}\left(\lambda_{\boldsymbol{j}}+\beta_{\mathbf{1}}\boldsymbol{I}\left\{\boldsymbol{humidex_j}\quad>\quad threshold\right\}\right) \qquad (2)$$

where Y_j is the hospital admission count on day j, P_j is the population, λ_j is the morbidity incidence rate of a non-heat day, β_1 is the change in hospital admission rate on a heat day, and $I\{humidex_j > threshold\}$ is the indicator of a heat day. This approach modeled the expected admission count after controlling for yearly population growth.

Time series analysis—A Poisson regression model was built to explore the relationship between humidex and hospitalization rates. Similar to previous work (24, 30, 16, 33), we used nonparametric splines to model the log-admission rate over time and humidex. Specifically, we assumed that:

$$\begin{aligned}&\boldsymbol{Y_{\tilde{j}}Poisson}\left(\boldsymbol{P_j}\lambda_{\boldsymbol{j}}\right),\textbf{with}\\&\boldsymbol{log}\quad \mu_{\mathbf{j}}=\beta_{\mathbf{0}}+\boldsymbol{s}\left(\boldsymbol{h_j}\right)+\boldsymbol{s}\left(\boldsymbol{t_j}\right)+\sum_{l=1}^{6}\beta_l\boldsymbol{I}_{\{week_j=l\}}+\sum_{l=6}^{9}\beta_l\boldsymbol{I}_{\{month_j=l\}}\end{aligned} \qquad (3)$$

where μ_j is the expected hospitalization rate on day j, $s(h_j)$ is a penalized regression spline modeling the effects of humidex, $s(t_j)$ is a penalized regression spline modeling the temporal trend of admissions over 21 years, and (β_l's) are the adjustments for day of the week and seasonal monthly effects.

For purposes of increased interpretability and usefulness for public health practitioners and policymakers, we simplified the nonparametric spline model with a piece-wise approximation to summarize heat effect on morbidity. A penalized regression spline models heat effect on morbidity below a model-derived optimal threshold, while a linear piece summarize heat's effect on morbidity beyond the optimal threshold. The optimal humidex threshold was identified by exploring 0.1 degree incremental changes starting at 20 °C and continuing through 44 °C humidex to maximize the likelihood of the following model:

$$\boldsymbol{log}\quad \mu_{\boldsymbol{j}}=\beta_{\mathbf{0}}+\boldsymbol{s}\left(\hat{\boldsymbol{h}}_0-\boldsymbol{h_j}\right)+\beta_{\mathbf{1}}\left(\boldsymbol{h_j}-\hat{\boldsymbol{h}}_{\mathbf{0}}\right)_{+}+\boldsymbol{s}\left(\boldsymbol{t_j}\right)+\sum_{l=1}^{6}\beta_l\boldsymbol{I}_{\{week_j=l\}}+\sum_{l=6}^{9}\beta_l\boldsymbol{I}_{\{month_j=l\}} \qquad (4)$$

where h_j is the humidex value on day $\hat{h}_0$ is the optimal alert threshold, $s\left(\hat{h}_0 - h_j\right)$ is the penalized regression spline modeling effect below the optimal threshold, $s(t_j)$ is a penalized regression spline modeling the temporal trend of hospital admissions over 21 years, and (β_l's) are adjustments for day of the week and seasonal effects. A heat day was then defined as a day in which the humidex exceeded the optimal threshold. The impact of humidex intensity on hospital admissions was assessed by the slope of the line (β_1) above the optimal threshold. The "mgcv" and "GAM" packages were used with the statistical software R version 2.14.1 to determine the model's degrees of freedom for the temporal trend and to tune the threshold, respectively (34).

Effect modification with individual-level characteristics

Individual-level characteristic data, obtained from CHARS, were evaluated for differences in hospitalization risk. The analyzed covariates included age, gender, and socio-economic status (probable low SES, defined as cases where primary payer indicated Medicaid or Charity care for all-ages, or non-low SES). Additional admission characteristics, admission source (emergency room or other) and admission type (emergency or urgent), were analyzed as well. Effect modification was examined by adding each covariate into the model along with an interaction term. By testing the significance of the interaction between demographic variables and heat, we can identify whether specific subpopulations are more vulnerable to heat intensity effects. Hospitalization rates for all covariate groups, except age, were not adjusted by population size of the covariate group because the data were not available.

Other heat effects on morbidity

Additional heat effects that may influence hospitalization rates include: elevated night-time temperatures, the duration of heat events, lag effects between exposure and total health impacts, and synoptic weather types. Studies have found that cooler nighttime temperatures help to minimize the daily effect of heat on mortality (35) that lengthier heat events increase health risks (36, 8) and that for specific causes of hospitalization, lags between 0 and 2 days produced significant increases in admissions (14). Furthermore, the type of synoptic weather pattern has been shown to influence mortality (37, 38) and morbidity (39) rates on heat days.

This study evaluated the data to see if there was a "cool down effect," wherein warmer evenings (or an elevated minimum humidex) would contribute to an increase in hospitalizations beyond the effect of heat during a heat day (Equation 5) and whether the magnitude of humidex above the optimal alert threshold affected risk (Equation 6). A cool-down effect was explored using the following two models:

$$\boldsymbol{log} \quad \mu_{\boldsymbol{j}}=\beta_{\boldsymbol{0}}+\beta_{\boldsymbol{2}}\boldsymbol{difference} \tag{5}$$

$$\boldsymbol{log} \quad \mu_{\boldsymbol{j}}=\beta_{\boldsymbol{0}}+\beta_{\boldsymbol{1}}\boldsymbol{aboveThres}+\beta_{\boldsymbol{2}}\boldsymbol{difference} \tag{6}$$

where ***difference*** is defined as the daily maximum humidex - daily minimum humidex for a given heat day, and ***aboveThres*** is defined as the daily maximum humidex - threshold.

Similarly, this study examined the relationship between hospital admission count and duration (number of consecutive heat days) using the following two models:

$$\boldsymbol{log} \quad \beta_{\boldsymbol{j}}=\beta_0+\beta_{\boldsymbol{2}}\boldsymbol{duration} \qquad (7)$$

$$\boldsymbol{log} \quad \mu_{\boldsymbol{j}}=\beta_0+\beta_1\boldsymbol{aboveThres}+\beta_{\boldsymbol{2}}\boldsymbol{duration} \qquad (8)$$

where duration is defined as the day's order in a given heat event.

This study also investigated lag effects between humidex and hospitalization admissions. A lag effect is defined as the total heat effect on hospital admissions spread over time. We explored distributed lag effects using the following model described by Armstrong (40):

$$\boldsymbol{E}\left(\boldsymbol{Y}_{\boldsymbol{j}}\right)=\exp\left\{\alpha+\boldsymbol{f}\left(\boldsymbol{h}_{\tilde{\boldsymbol{j}}}\right)+\boldsymbol{covariates}+\boldsymbol{s}\left(\boldsymbol{time}\right)\right\}, \boldsymbol{f}\left(\boldsymbol{h}_{\tilde{\boldsymbol{j}}}\right)=\sum_{\mathbf{l=0}}^{\mathbf{L}}\beta_l\boldsymbol{h}_{\boldsymbol{j}-\boldsymbol{l}} \qquad (9)$$

where $\boldsymbol{Y_j}$ is the hospital admission count on day $\boldsymbol{j}$, $\boldsymbol{s}(\boldsymbol{time})$ is a spline curve over time, and $\boldsymbol{f}(\boldsymbol{h}_{\sim j})$ is a function of humidex values on days up to day $\boldsymbol{j}$. This model takes a weighted effect of humidex on day $\boldsymbol{j}$ and the previous $\boldsymbol{L}$ days. Using different constraints or temporal structures for $\boldsymbol{\beta_l}$, $\boldsymbol{l} = \mathbf{0}, \ldots, \boldsymbol{L}$, allows us to examine the evidence for lag effects. The lag model was implemented using the "dlnm" (distributed lag non-linear model) package in R version 2.14.1 (41).

Lastly, we investigated whether the classification of synoptic weather type, on a given heat day, affected hospital admission rates. Moist and dry tropical weather types have been found to be associated with increased mortality (42, 38) and morbidity (39). Using daily spatial synoptic weather type classification data for the Seattle/Tacoma station (43), effect modification was explored by applying the same method used for individual-level characteristics.

Results

King County population and climate

King is the largest county in the Pacific Northwest, is the 14th largest county in the United States, and accounts for approximately 30% of the state's population throughout the study's time frame (27, 23). From 1990 to 2010 the county's population increased 28%, with age groups 45-64, 65-84, and 85+ increasing 88%, 19%, 101%, respectively (Table 2). King County is located in Western Washington and is characterized by relatively cool summers. Its summer daily average humidex values range from a minimum of 6.90 °C (44.4 °F) to a maximum of 22.6 °C (72.7 °F) (Table 3).

From 1990 to 2010, King County experienced 752,151 unplanned hospitalizations during the warmer months of May-September, 54% of the overall, non-traumatic admission count. On average, there were 234 admissions per day, with a length of stay averaging 5 days (Table 2). Over the 21-year study time frame, total hospital charges in King County have increased 6-fold, with no adjustment for inflation. Over 1990-2010, the average cost per day of stay was $3,388, while the average total cost for all of King County was approximately 4 million dollars per day. Table 2 provides descriptive demographic data by age and percent change in population from 1990-2010, as well as data on admission counts and costs from 1990-2010. Table 3 describes meteorological data ranges for all days studied, heat days above the relative risk threshold (36.2 °C), and heat days above the time series threshold (37.4 °C) from 1990-2010.

Association between humidex and morbidity

Relative risk analysis—A heat day was defined by Equation (2) as a day that exceeded the 99th percentile of all days, January-December (36.2 °C (97.2 °F) humidex). During 1990-2010, King County experienced 77 days over the 99th percentile, 2.4% of all May-September days. The average humidex on heat days was 38.7 °C (101.7 °F) (Table 3). Relative risk estimates and 95% confidence intervals for all age groups and categories of admissions are reported in Table 4. For all-ages, unplanned, non-traumatic hospital admissions increased by 2% (non-statistically significant) on a heat day compared to a non-heat day. Statistically significant increases in admissions for all ages were found in the following subcategories of non-traumatic causes: 57% for nephritis and nephrotic syndromes, 68% for acute renal failure, and 244% for natural heat exposure (including dehydration). To achieve a better understanding of the relative burden of hospitalization, the proportional morbidity is illustrated in Figure 1. Cause-of-admission categories run along the abscissa, while the corresponding relative risk estimates are reflected by the ordinate. Figure 1 illustrates the proportion of all-ages hospital admission for each cause, in relation to all non-traumatic causes of admission on heat days (e.g. circulatory causes-of-admission account for approximately 20% of all hospitalizations on a heat day).

When investigating hospitalizations stratified by cause and age, significant increases in risk were found for the: 0-4 age group, mental disorders (318%); the 15-44 age group, natural heat exposure (399%); the 45-64 age group, nephritis and nephrotic syndromes (76%) , acute renal failure (99%), and natural heat exposure (142%); the 65-84 age group, nephritis and nephrotic syndromes (60%), acute renal failure (67%), and natural heat exposure (242%); and the 85+ age group, all non-traumatic (8%), nephritis and nephrotic syndromes (49%), acute renal failure (55%) and natural heat exposure (343%). The 0-4 age group's mental disorders estimate should be considered with caution, given relatively small numbers and the difficulty of diagnosing mental conditions in this age category. It should also be noted that both the 15-44 and 45-64 age groups' natural heat exposure estimates are based on a small number of cases, as reported in Table 4.

To achieve a better understanding of the relative burden of hospitalizations stratified by age and cause of admission, the proportional morbidity is illustrated in Figure 2. Figure 2 illustrates the proportion of morbidity for each age-adjusted cause, in relation to the age-adjusted, non-traumatic hospital admissions on heat days. For example, acute renal failure accounts for 3% of all hospital admissions in the 85+ age group, while the non-traumatic 85+ bubble represents the proportion of admissions (10%) of all-ages non-traumatic admissions, on a heat day.)

Time series analysis—In King County, the time series relationship between humidex and log-admission rates is J-shaped when estimated by continuous splines. The relationship illustrates an increased risk of morbidity from exposure to humidex exceeding approximately 33 °C humidex. A piece-wise linear approximation was used to summarize heat effect on hospital admissions. The optimal threshold was determined by increasing the model by 0.1 °C until the maximum likelihood was identified. The optimal threshold is 1.2 °C above the 99th percentile at 37.4 °C (99.3 °F) (Figure 3). Between 1990 and 2010, King County experienced 50 days that exceeded the time series analysis threshold. The average humidex on these exceedance days was 39.7 °C (103.5 °F) (Table 2). Figure 3 illustrates the nonparametric spline model and corresponding piece-wise linear approximation for King County's unplanned, non-traumatic log-hospitalization rate and humidex relationship.

Intensity estimates and 95% confidence intervals for all age groups and categories of hospital admission are reported in Table 5. For all-ages, all non-traumatic causes, we observed a 1.6% increase in hospitalizations per degree increase in average county-wide daily maximum humidex above 37.4 °C. Statistically significant increases in hospitalizations for all ages were found for respiratory (2.3%), nephritis and nephrotic syndromes (6.8%), acute renal failure (7.6%), and natural heat exposure (17.5%). When investigating morbidity stratified by cause and age, statistically significant results were found for the: 15-44 age group, COPD (10.0%) and asthma (11.8%); the 45-64 age group, cardiovascular (−4.3%), nephritis and nephrotic syndromes (9.5%), and acute renal failure (9.2%); the 65-84 age group, all non-traumatic (1.6%), nephritis and nephrotic syndromes (8.5%), acute renal failure (8.5%), and natural heat exposure (18.3%); and the 85+ age group, all non-traumatic (6.3%), circulatory (4.8%), cardiovascular (4.4%), respiratory (10.0%), COPD (17.4%), and natural heat exposure (27.5%). It should be noted that the 85+ group's natural heat exposure estimate is based on a small number of cases, as reported in Table 5.

Effect modification with individual-level characteristics—We did not find that gender or socio-economic status altered the risk of hospitalization on a heat day, nor did we find differences stratified by admission source or admission type. We did, however, find that age had a statistically significant influence on a person's risk of being admitted to a hospital on a heat day. In both the relative risk and time series analysis we found the 85+ age group to be at greatest risk for all non-traumatic causes of admission.

Other heat effects on hospitalization—We did not find a statistically significant effect on admissions when considering the range between minimum and maximum humidex (cool-down effect) or from the number of consecutive heat days above threshold (duration effect). Likewise, we did not find a significant lag relationship between humidex and hospitalizations where total effect was spread over several days. Lastly, the type of synoptic weather type classification was not found to be associated with hospitalization rates.

Discussion

This study's results demonstrate that heat, expressed as humidex, is associated with increased hospital admissions on heat days, and that the risk increases with heat's intensity.

Our study is unique in that provides the opportunity to compare two ways of defining a heat day: a relative threshold calculated from a fixed percentile, and an absolute threshold estimated using a fitted model. We believe the results provide a more complete picture of regional heat effects. The relative risk analysis captures heat's overall contribution to excess morbidity on heat days, while the time series analysis allows for a nuanced understanding of the effect of heat on hospitalization and the role of potential effect modifiers.

Overall association between humidex and morbidity

This study did not find a statistically significant increase in all-age, all non-traumatic hospitalizations for both analyses. The relative risk of hospitalization on a heat day was 2% (statistically non-significant) greater than on a non-heat day, with risk increasing 1.59% (statistically significant) for each degree increase in humidex above 37.4 °C. Knowlton et al. (12) found a statistically non-significant 1% increase in the relative risk of California hospitalizations on a heat wave day, compared to a non-heat wave day, while Kovats, Hajat and Wilkinson (44) also found a non-significant 2.6% increase in London hospitalizations on a heat wave day. When investigating a log-linear increase in morbidity above an absolute threshold, Linares and Diaz (45) found a statistically significant, 4.6%, increase in unplanned, hospital admissions for each degree increase in maximum daily temperature above 36.6 °C in Madrid, Spain.

Heat-health association stratified by cause

When we stratified all ages by cause of hospital admission, both relative risk and time series analyses showed statistically significant increases in risk for nephritis and nephrotic syndromes, acute renal failure, and natural heat exposure. Additionally, our time series analysis found a statistically significant increase in all-ages respiratory-related hospitalizations. Comparatively, Knowlton et al. (12) found all-age hospitalizations increased by 5% for nephritis and nephrotic syndromes, 11% for acute renal failure, 950% for heat-related illness, and 9% for electrolyte imbalance, during the July 15 - August 1, 2006 California heat wave as compared to a referent period. Li et al. (46) also found comparable time series estimates for endocrine (1.09%), genitourinary (1.12%) and renal failure (1.13%) causes of hospitalization considering the results are per degree increase above a lower (29.5 °C) threshold.

Heat-health association stratified by cause and age

When stratifying cause-of-admission categories by age group, we found with the relative risk analysis that heat's overall effect does not exclusively impact the elderly (85+) age group. Rather, the results suggest hospitalizations impact a younger population (45-64 and 65-84 age groups). Similar younger age-vulnerable populations were found when we examined the relative risk of mortality associated with extreme heat in King County, Washington (30). With the time series analysis, our results also show that heat affects the younger age groups (15-44, 45-64, and 65-84). This is contrary to what we have found with mortality (30), where heat intensity almost exclusively affected the 85+ age group. Similarly, Li et al. (46) found statistically significant heat-hospital admission relationships for Milwaukee's 15-64, 75-84 and the 85+ age groups.

This study continues to highlight the vulnerability of the elderly (85+) population to circulatory health outcomes. The same general modeling approach and geographic study area was used in our previous analysis of heat and mortality (30). Our mortality results, showing increased circulatory (4.1%) and cardiovascular deaths (4.3%) with each degree increase in humidex above the threshold (36.0 °C), parallel the association we found between increased circulatory (4.8%) and cardiovascular hospitalizations (4.4%) per degree above threshold. It has been hypothesized that the time between heat exposure and resulting cardiovascular death is short (45), and that social isolation increases the risk of death (44, 45, 47). It has also been found that cardiovascular mortality observed on extreme heat days was higher for out-of-hospital deaths than in-hospital deaths (48). Our mortality (30) and this paper's morbidity findings suggest that the impact of extreme heat on cardiovascular health is much greater than any one study finding taken alone.

Results from both analyses in this study identify a non-elderly population vulnerable due to renal-impairment. For the 45-64 year-old age group, we found that the relative risk of hospitalization on a heat day from nephritis and nephrotic syndromes was 76%, with risk increasing 9.5% for each degree increase in humidex above 37.4 °C. Similarly, this age group experienced a 99% increased risk of acute renal failure admissions, with risk increasing 9.2% for each degree increase in humidex above 37.4 °C. With both analyses, we found significant increases in nephritis and nephrotic syndromes and acute kidney failure hospitalizations for the 65-84 year-old age group as well, although not as large. While our mortality (30) analysis did not find a parallel increase in nephritis and nephrotic syndromes and acute renal failure, we did find that for the 45-64 year-old age group a 78% greater risk of death from diabetes was observed on a heat day compared to a non-heat day, with risk increasing 14.22% for each degree increase in humidex above 36.0 °C.

Hansen et al. (49) found that 15-64 year-olds living in Adelaide, Australia, had a 13% increased risk of hospitalization for renal disease and a 25% increased risk for acute renal failure during heat wave days (compared to non-heat wave days), while diabetic females 50-54 and 85+ years of age were at an increased risk for hospitalization due to renal disease. In California, Ostro et al.'s (15) meta-analysis found an elevated risk of diabetes and acute renal failure hospitalizations (4% and 10.2%, respectively), while in New York, five of the 13 climate zones analyzed showed statistically significant increases in hospitalizations from acute renal failure (14). In our study, we did not have access to comorbidity data, such as diabetes prevalence. However, with roughly 44% of new kidney-failure cases nationwide originating from diabetic patients (50), our findings suggest that King County's diabetic population could be at an increased risk for kidney-related health outcomes. Given that 8% of 45-64 year-olds and 15% of 65+ year-olds living in King County are estimated to have diabetes, our findings are an important consideration for outreach and prevention programs (51).

Effect modification

Aside from age, this study did not find that the individual-level covariates of gender, admission source, admission type, and socio-economic status, modified the effect of heat on hospitalizations. Other individual-level characteristics, not collected by CHARS, may be more relevant predictors of vulnerability to heat-related morbidity. Studies have found that race and ethnicity (14), income level (33), educational achievement, and social isolation affect risks for hospitalization and death (21, 48). An alternative explanation for the lack of identified vulnerable populations in this study could derive from our region's low prevalence of air conditioning. Hamlet et al. (52) has estimated an 8% air conditioning prevalence rate in King County. Studies have demonstrated that the availability and use of air conditioning is a protective factor against heat-related mortality (21, 3, 53). It is possible that our region's nearly universal lack of residential air conditioning is masking an otherwise observable vulnerable population.

This study found that the same-day humidex exposure had the strongest association with hospitalization, and that there was no evidence of a lag, duration, or cool-down effects. These findings are not unprecedented and are similar to other studies in which either the same-day apparent temperature (18) or recent lags of 0-2 days were found to be most relevant to the heat-morbidity relationship (14).

This study did not adjust for air pollutants, as we were interested in estimating the total effect of heat on morbidity rather than just the direct effect. Furthermore, a recent commentary by Buckley, Samet and Richardson (54) noted that adjustment for air pollutants should be conducted with caution and clear rationale, as controlling for non-confounders can lead to biased estimates of heat effects. Several studies have adjusted for air pollution (33, 46, 44) but lacked a sensitivity analysis comparing adjusted to unadjusted rates or estimates of effect modification. Green et al. (18) adjusted for ozone and PM2.5 in their analysis of 9 California counties and observed slight decreases in hospitalization risks for all-respiratory diseases and pneumonia compared to unadjusted rates, while finding slight increases in hospitalization for ischemic stroke and diabetes. Comparatively, mortality outcome studies have found that the association between heat and mortality persists even after controlling for air pollutants (6, 5, 55).

Limitations

Limitations of this study include possible exposure misclassification and inappropriate geographical boundary selection. Our study uses a daily county-wide averaged maximum humidex value to estimate heat exposure. Averaging across a large geographical space may result in exposure misclassification when a disproportionate number of cases are below or above the average maximum humidex value. Improved exposure assessment might be obtained by using a population-weighted humidex value. However, a population-weighted average is difficult to estimate over 31 years, given significant changes in the County's demographics. Conversely, a county-wide humidex is historically stable over the study's time frame. Another potential exposure metric could be calculated by assigning each case a maximum humidex value based on the closest meteorological grid center point to the hospital utilized. Additionally, data regarding access to air conditioning, behavioral/lifestyle choices and community-level characteristics would further refine heat exposure. In this study, humidex was calculated using an average daily relative humidity. It is possible that by using the average daily relative humidity, our model threshold may be higher than the true heat-health threshold. However, even if our metric is biased high, it is still below the current

National Weather Service warning criteria for this region. This study used political jurisdictions (county boundary) to assess the heat-morbidity relationship. This geographical unit of analysis may not accurately reflect how the effects of heat on hospitalization vary spatially. An alternative method, and area for future research, would be to combine populations that experience similar climate zones and therefore should have similar levels of acclimatization. An example of this type of analysis is provided by Lin et al. (33); they examined 14 different New York State climate regions for associations with excessive heat and respiratory hospitalizations, and then predicted future health burdens given climate change.

This study did not correct for multiple comparisons. A Type 1 error may occur when numerous subgroups are analyzed for effect difference. The more comparisons that are analyzed, the more opportunity there is to identify, by chance, a result that appears significant, even when no statistically significant difference exists. A multiple testing correction, such as Bonferroni, could be applied to our analyses (56). Instead, we progressively analyzed our data; looking at overall, all-age results prior to analyzing sub-categories of cause and age. The statistically significant results were then examined for expected dose-response patterns, concurrence with existing literature, and influence of small counts. Results were flagged in data presentation and discussion when found to depend on a small number of outcomes (N<20).

Conclusion

This study characterized King County, Washington’s historic heat-morbidity relationship using two different statistical methods. Our study is novel, in that it comprehensively examines heat effect on hospital admissions in a temperate climate. The results demonstrate that heat, expressed as humidex, is associated with increased hospitalizations on heat days, and that the risk increases with heat intensity. This study found that in addition to the elderly (85+), younger age groups have an increased relative risk of hospitalization for several of the admission categories, particularly: nephritis and nephrotic syndromes, acute renal failure, and natural heat exposure. When considering heat’s intensity, we found effects on health outcomes in age groups as young as 15-44 years-old; this contrasts with our mortality findings, where intensity almost exclusively affected the 85+ age group. Individual-level characteristics (age being an exception) and other heat effects from nighttime cooling, heat-event duration, lag effects, and synoptic weather type classification were not found to affect hospitalization rates.

Our study of hospital admissions intended to estimate heat’s effect on morbidity. The results, however, point to an incomplete estimation, where only the advancement of diseases serious enough to require hospitalization have been captured. Future work is needed to estimate heat-health outcome relationships that precede hospitalization or that are not serious enough to require admission. Future research is also needed to validate the methods used to model our heat-morbidity relationship, as our piece-wise linear model fits a linear slope to an otherwise non-linear relationship. Consideration should be given to the overall circulatory health of the 85+ population on extreme heat days, as improvements would affect both hospitalization admission and mortality rates. Lastly, our findings warrant additional investigation into the role heat exposure plays in the diabetic patient's health and care, as well as the connection between diabetes and renal syndromes in our area.

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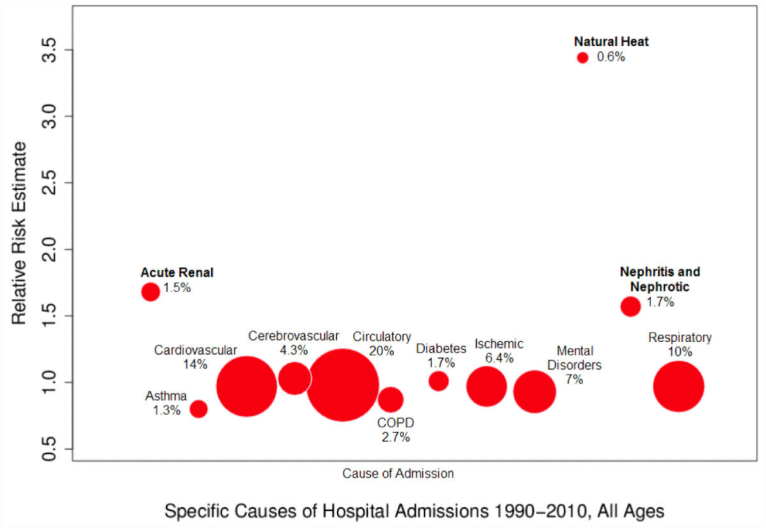

Fig. 1.

Proportional cause-of-hospitalization burden in relation to total morbidity, on 1% heat days; Size of bubbles represent proportion of admissions compared to all non-traumatic admissions, while placement on the y-axis represents the relative risk estimate; Statistically significant causes of all-ages admission are indicated in bold

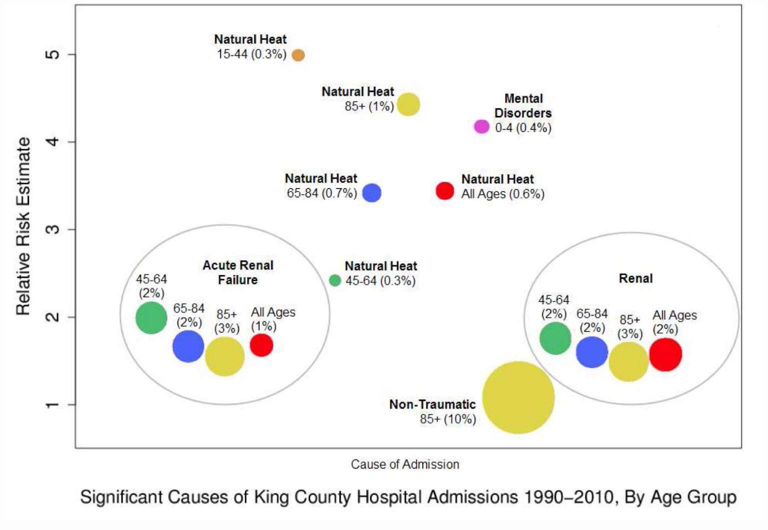

Fig. 2.

Proportional cause-of-hospitalization burden in relation to total admissions, on 1% heat days, by statistically significant age category; Area of bubbles represent proportion of age-adjusted hospitalizations compared to non-traumatic causes, while placement on the y-axis represents hosptial admission relative risk estimate

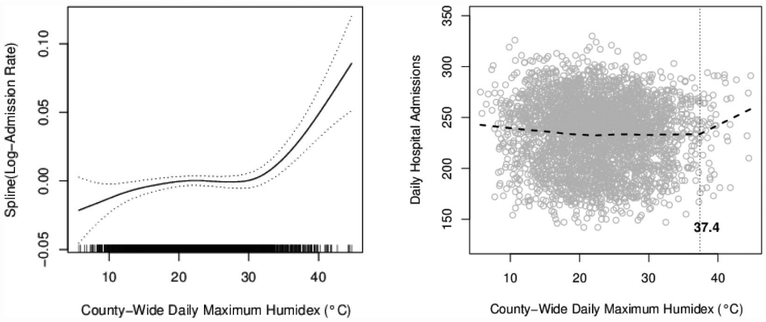

Fig. 3.

Nonparametric spline model of unplanned, non-traumatic log-hospital admission rate and humidex relationship; (right) corresponding piecewise approximation using a natural spline below the optimal threshold and a linear piece above 37.4 °C Humidex

Table 1

Underlying causes of hospital admissions and associated admission International Classification of Disease (ICD)-9-CM codes

Category	ICD-9 Code
Non-Traumatic	001-799
Select Non-Traumatic Causes	
Diabetes	250
Circulatory	390-459
Cardiovascular	393-429
Ischemic	410-414
Cerebrovascular	430-438
Respiratory	460-519
COPD and allied conditions	490-496
Asthma	493
Nephritis and Nephrotic[1]	580-589
Acute Renal Failure	584
Mental Disorders	290-316
Select Traumatic Cause	
Natural Heat Exposure w/Dehydration[2]	E900.0, E900.9, 992, & 276.51

[1] Nephritis and Nephrotic syndromes and acute renal failure have been found to be a significant cause of hospital admissions associated with extreme heat events. (Mastrangelo et. al. 2007, Hansen et al. 2008, Knowlton et al. 2008, Reid et al. 2012, Lin et al. 2012)

[2] While morbidity attributed to natural heat-related exposure is classified as a traumatic external injury, we have included the non-traumatic dehydration code ICD-9-CM 276.51 with this sub-grouping.

Table 2

Descriptive data: population demographics, admission counts and costs for King County, Washington, 1990–2010

Census Population			
	1990[1]	**2010** [1] **(% Change)**	
State Total	4,866,692	6,724,540 (38.2%)	
King County Total	1,507,319	1,931,249 (28.1%)	
% of State Population	30.9%	28.7% (−7.0%)	
0-4	106,999	120,294 (12.4%)	
5-14	185,933	224,084 (20.5%)	
15-44	772,361	856,843 (10.9%)	
45-64	276,070	519,349 (88.1%)	
65-84	149,170	176,895 (18.6%)	
85+	16,786	33,784 (101%)	
King County Hospital Admissions			
	1990-2010	**1990**	**2010**
Total non-traumatic admissions	1,384,251	64,774	77,765
Total unplanned admissions n (% of total)	752,151 (54%)	34,194 (53%)	46,255 (59%)
Average daily admission rate	234 admin/day	219 admin/day	250 admin/day
Average length of admission stay	5.01 days	6.2 days	5.0 days
Average charge/day of stay	$3,389/day	$1,072/day	$7,328/day
Total hospital charges/day	$3.97 million	$1.5 million	$9.2 million
Individual-level Characteristics			
Gender	**Male**	**Female**	
n (% of total)	419,861 (55.8%)	332,285 (44.2%)	
Socio Economic Status	**Probable low SES**[2]	**Non-low SES**	
n (% of total)	121,844 (16.2%)	630,307 (83.8%)	
Other Admission Characteristics			
Admission Source	**Emergency room**	**Other**	
n (% of total)	476,698 (63.4%)	275,453 (36.6%)	
Admission Type	**Emergency**	**Urgent**	
n (% of total)	486,195 (64.6%)	265,956 (35.4%)	

[1] Source: Washington State Department of Health

[2] Probable Low SES was defined as cases where primary payer indicated Medicaid (all ages,) or Charity care (all ages.)

Table 3

Meteorological descriptive data for King County, Washington, 1990–2010

Meteorological Data (1990-2010, May-Sept.)	
County-Wide Humidex across all years	**°C (°F)**
Minimum	6.90 °C (44.4 °F)
Maximum	22.6 °C (72.7 °F)
Heat Days above Relative Risk Threshold	**n days (% of days)**
99th percentile 36.2 °C (97.2 °F)	77 days (2.4%)
County-Wide Maximum across all years	**°C (°F)**
Humidex	38.7 °C (101.7 °F)
Temperature	30.8 °C (87.4 °F)
Heat Days above Time Series Threshold	**n days (% of days)**
37.4 °C (99.3 °F)	50 days (1.6 %)
County-Wide Maximum across all years	**°C (°F)**
Humidex	39.7 °C (103.5 °F)
Temperature	31.4 °C (88.5 °F)

Table 4

Relative risk analysis results: Increased risk (95% CI) in hospital admissions on a 99th percentile (36.2 °C) heat day compared to a non-heat day, by age group and cause of admission [1]

	All Ages	0-4	5-14	15-44	45-64	65-84	85+
Non-Traumatic	1.02 (0.98, 1.05)	0.98 (0.9, 1.06)	0.97 (0.88, 1.08)	0.99 (0.93, 1.05)	1.03 (0.98, 1.07)	1.01 (0.97, 1.05)	**1.08** **(1.03, 1.14)**
Select Non-Traumatic Causes							
Diabetes	1.01 (0.9, 1.14)	0.22 (0.03, 1.65)	1.07 (0.71, 1.63)	0.99 (0.82, 1.19)	1.11 (0.91, 1.35)	0.95 (0.74, 1.23)	0.78 (0.37, 1.66)
Circulatory	0.98 (0.93, 1.02)	0.86 (0.52, 1.44)	1.03 (0.6, 1.79)	0.96 (0.85, 1.08)	0.98 (0.9, 1.06)	0.95 (0.89, 1.01)	1.01 (0.92, 1.1)
Cardiovascular	0.97 (0.91, 1.02)	0.92 (0.47, 1.8)	1.03 (0.48, 2.18)	0.97 (0.84, 1.12)	0.92 (0.84, 1.01)	0.96 (0.89, 1.04)	1.01 (0.91, 1.13)
Ischemic	0.97 (0.89, 1.06)	--	--	1.02 (0.79, 1.31)	0.93 (0.81, 1.07)	0.97 (0.87, 1.09)	1.01 (0.82, 1.23)
Cerebrovascular	1.03 (0.96, 1.1)	1.35 (0.33, 5.44)	0.87 (0.21, 3.54)	0.96 (0.72, 1.29)	1.14 (1, 1.31)	0.96 (0.87, 1.07)	1.02 (0.86, 1.21)
Respiratory	0.97 (0.91, 1.03)	0.71 (0.58, 0.86)	0.67 (0.49, 0.91)	1.05 0.93, 1.19)	0.99 (0.9, 1.1)	0.97 (0.89, 1.05)	1.11 (0.97, 1.25)
COPD	0.87 (0.78, 0.97)	0.68 (0.51, 0.9)	0.54 (0.35, 0.85)	1.04 (0.81, 1.32)	0.96 (0.8, 1.15)	0.88 (0.75, 1.03)	1.21 (0.86, 1.69)
Asthma	0.8 (0.68, 0.94)	0.68 0.51, 0.91)	0.55 (0.35, 0.86)	0.98 (0.75, 1.28)	0.95 (0.7, 1.28)	0.93 0.65, 1.32)	1.11 (0.53, 2.34)
Nephritis and Nephrotic	**1.57** **(1.35, 1.83)**	0.46 (0.06, 3.25)	1.68 (0.69, 4.11)	1.13 (0.78, 1.63)	**1.76** **(1.42, 2.18)**	**1.6** **(1.3, 1.97)**	**1.49** **(1.12, 1.99)**
Acute Renal Failure	**1.68** **(1.41, 2.01)**	1.84 (0.25, 13.38)	--	0.99 (0.58, 1.69)	**1.99** **(1.58, 2.5)**	**1.67** **(1.34, 2.07)**	**1.55** **(1.16, 2.07)**
Mental Disorders	0.93 (0.83, 1.03)	**4.18** **(1.29, 3.57)**[2]	0.82 (0.6, 1.11)	0.92 (0.82, 1.03)	0.92 (0.8, 1.06)	1.05 (0.86, 1.28)	0.76 (0.48, 1.2)
Select Traumatic Cause							

	All Ages	0-4	5-14	15-44	45-64	65-84	85+
Natural Heat Exposure w/Dehydration	**3.44** **(2.56, 4.64)**	1.96 (0.76, 5.03)	2.52 (0.76, 8.32)	**4.99** **(2.89, 8.6)**[3]	**2.42** **(1.45, 4.06)**[4]	**3.42** **(2.3, 5.08)**	**4.43** **(2.99, 6.56)**

[1] Bolded relative risk values are significantly greater than 1 ($p < 0.05$) ; -- indicates too few cases available to calculate

[2] While statistically significant, the estimate is based on a small number of cases [103 cases on non-heat days, 5 cases on a heat day]

[3] While statistically significant, the estimate is based on a small number of cases [139 cases on non-heat days, 17 cases on a heat day]

[4] While statistically significant, the estimate is based on a small number of cases [264 cases on non-heat days, 16 cases on a heat day]

Table 5

Time series analysis results: Percentage (95% CI) increase or decrease in morbidity per degree increase in humidex °C above 37.4 °C, by age group and underlying cause of admission[1]

	All Ages	0-4	5-14	15-44	45-64	65-84	85+
Non-traumatic	**1.6 % (0.9 %, 2.3%)**	1.1% (−2.3%, 4.7%)	1.2% (−3.1%, 5.7%)	0.6% (−0.7%, 1.9%)	1.0% (−0.4%, 2.4%)	**1.6% (0.3%, 3.0%)**	**6.3% (4.1%, 8.5%)**
Diabetes	−1.2% (−5.8%, 3.6%)	−21.9% (−64.5%, 71.6%)	−11.9% (−30.3%, 11.5%)	−0.8% (−8.5%, 7.6%)	−2.1% (−10.0%, 6.6%)	2.6% (−6.8%, 13.0%)	−3.0% (−28.6%, 31.7%)
Circulatory	0.2% (−1.3%, 1.6%)	−2.0% (−22.4%, 23.9%)	15.8% (−3.6%, 38.6%)	−0.6% (−5.5%, 4.7%)	−2.2% (−4.8%, 0.5%)	−0.02% (−2.1%, 2.1%)	**4.8% (1.4%, 8.3%)**
Cardiovascular	−0.2% (−2.0%, 1.5%)	−14.6% (−43.0%, 27.9%)	2.2% (−26.8%, 42.9%)	−1.2% (−7.4%, 5.4%)	**−4.3% (−7.4%, −1.0%)**	1.1% (−1.4%, 3.6%)	**4.4% (0.2%, 8.9%)**
Ischemic	1.5% (−1.1 %, 4.1%)	--	--	−1.6% (−13.7%, 12.0%)	−0.6% (−5.2%, 4.2%)	2.3% (−1.8%, 6.6%)	7.1% (−1.3%, 16.3%)
Cerebrovascular	0.6 % (−2.3%, 3.6%)	−19.4% (−73.3%, 143%)	2.0% (−37.8%, 67.3%)	2.3% (−9.0%, 14.9%)	2.2% (−3.4%, 8.2%)	−2.2% (−6.5%, 2.3%)	4.4% (−1.7%, 11%)
Respiratory	**2.3% (0.4%, 4.3%)**	−4.9% (−12.5%, 3.3%)	−3.0% (−13.6%, 9%)	4.7% (−0.5%, 10.1%)	3.5% (−0.5%, 7.7%)	−1.2% (−4.6%, 2.3%)	**10.0% (5.2%, 14.9%)**
COPD	3.4% (−0.5%, 7.4%)	−4.4% (−15.2%, 7.8%)	−9.2% (−24.5%, 9.4%)	10.0% (0.02%, 21%)	4.8% (−2.6%, 12.7%)	1.1% (−5.7%, 8.5%)	17.4% (4.8%, 31.5%)
Asthma	5.0% (−0.7%, 11 %)	−1.0% (−12.0%, 11.5%)	−5.6% (−21.3%, 13.4%)	11.8% (0.5%, 24.3%)	8.3% (−3.3%, 21.2%)	4.6% (−10.5%, 22.2%)	19.4% (−7.1%, 53.4%)
Nephritis and Nephrotic	6.8% (2.6%, 11.1%)	−25.6% (−82.5%, 216%)	−15.6% (−53.5%, 53.3%)	−7.1% (−21.4%, 9.8%)	9.5% (1.8%, 17.9%)	8.5% (1.8%, 15.6%)	7.2% (−2.9%, 18.3%)
Acute renal failure	7.6% (3.2%, 12.2%)	11.5% (−66.8%, 275%)	--	−3.5% (−22.0%, 19.4%)	9.2% (0.5%, 18.7%)	8.5% (1.2%, 16.3%)	7.1% (−3.7%, 19.2%)
Mental Disorders	1.9% (−0.5%, 4.4%)	17.8% (−31.4%, 102%)	−11% (−23.6%, 3.8%)	2.2% (−0.9%, 5.4%)	2.4% (−2.3%, 7.3%)	2.4% (−5.5%, 10.9%)	2.3% (−13.1%, 20.4%)

	All Ages	0-4	5-14	15-44	45-64	65-84	85+
Natural Heat Exposure w/dehydration	**17.5% (12.1%, 23.1%)**	17.7% (−4.2%, 44.5%)	21.2% (−1.8%, 49.8%)	10.0% (−3.5%, 25.3%)	4.9% (−7.1%, 18.3%)	**18.3% (10.7%, 26.4%)**	**27.5% (17.8%,38.1%)**[2]

[1] Bolded time series estimates are significantly greater than 0 ($p < 0.05$) ; -- indicates too few cases available to calculate; results have been rounded to 1 decimal place

[2] While statistically significant, the estimate is based on a small number of cases [230 cases on non-heat days, 18 cases on a heat day]