Tania Busch Isaksen*, Michael G. Yost, Elizabeth K. Hom, You Ren, Hilary Lyons and Richard A. Fenske

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

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 historic (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, whereas a time series analysis using a piecewise linear model approximation was used to estimate the effect of heat intensity 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 vs. a non-heat day, was noted for all-ages and all non-traumatic causes. When considering the effect of heat intensity 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 age groups (<85 years) experience significant risk for nephritis and nephrotic syndromes, acute renal failure, natural heat exposure, chronic obstructive pulmonary disease, and asthma hospitalizations.

Keywords: climate change; extreme heat; humidex; morbidity; Pacific Northwest.

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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 indicated that higher temperatures, or other indices of the physiologic effect of heat and humidity, are associated with increased mortality (2–8). Research focused on hospitalization and emergency room visits also found an increased risk associated with increasing temperatures (9–13). Studies conducted in the US have shown an increased risk of hospitalization for diverse conditions like 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 modify the heat's effect on mortality (4, 8) and morbidity (14). Socio-demographic factors that have been found to influence mortality and morbidity risks include social isolation (3, 19), socioeconomic status (19, 20), and ethnicity and educational status (14, 21). 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. Given that 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 those that were specifically requested by the local health jurisdiction. A second analysis, which used 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. Finally, 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.

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[a]	580–589
Acute renal failure	584
Mental disorders	290–316
Select traumatic cause	
Natural heat exposure w/ dehydration[b]	E900.0, E900.9, 992, and 276.51

[a]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. (11), Hansen et al. (27), Knowlton et al. (12), Reid et al. 2012 (28), Lin et al. (29)].
[b]Although 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.

Materials and methods

Hospital admissions and population data

King County hospital discharge data for all non-traumatic illnesses and external injury due to heat causes from 1990 to 2010 were obtained from the Comprehensive Hospital Abstract Reporting System (CHARS) maintained by the Washington State Department of Health. 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, and a total of 3213 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; of these, 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 and chronic obstructive pulmonary disease (COPD); asthma, nephritis and nephritic; 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. These characteristics include age, gender, and socioeconomic 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, and 85+ years) were obtained from the Washington State Office of Financial Management (OFM) (30).

Meteorology data

This study used a gridded (1/16° resolution) meteorologic data set produced by the University of Washington's Climate Impacts Group (31). Meteorologic values were derived by combining the most current knowledge on regional and spatial climatic patterns with land-surface meteorologic 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 (32), whereas the meteorologic 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, 33), we used humidex as the measure of exposure. Humidex is an apparent temperature index, which measures the combined effects of temperature and humidity on the human body (34). 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:

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

where T is the air temperature (degrees Celsius), H is the average relative humidity (%), and ν is the vapor pressure (kPa) (35). 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 exceeded 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:

$$E(Y_j)=P_j(\lambda_j+\beta_1 I\{\text{humidex}_j>\text{threshold}\}), \quad [2]$$

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 $I\{\text{humidex}_j>\text{threshold}\}$ 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 works (16, 24, 29, 33), we used nonparametric splines to model the log-admission rate over time and humidex. Specifically, we assumed that:

$$\begin{aligned}&Y_j\sim\text{Poisson}(P_j\lambda_j),\text{with}\\&\log\mu_j=\beta_0+s(h_j)+s(t_j)+\sum_{l=1}^{6}\beta_l I_{\{\text{week}_j=l\}}+\sum_{l=6}^{9}\beta_l I_{\{\text{month}_j=l\}},\end{aligned} \quad [3]$$

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 ($\beta_l s$) 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 piecewise approximation to summarize heat effect on morbidity. A penalized regression spline models heat effect on morbidity below a model-derived optimal threshold, whereas a linear piece summarizes the effect of heat 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:

$$\begin{aligned}\log\mu_j=&\beta_0+s(\hat{h}_0-h_j)+\beta_1(h_j-\hat{h}_0)+s(t_j)\\&+\sum_{l=1}^{6}\beta_l I_{\{\text{week}_j=l\}}+\sum_{l=6}^{9}\beta_l I_{\{\text{month}_j=l\}},\end{aligned} \quad [4]$$

where h_j is the humidex value on day j, $\hat{h}_0$ is the optimal alert threshold, $s(\hat{h}_0-h_j)$ 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 ($\beta_l s$) 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 statistic software R version 2.14.1 to determine the model's degrees of freedom for the temporal trend and to tune the threshold, respectively (36).

Effect modification with individual-level characteristics

Individual-level characteristic data, which were obtained from CHARS, were evaluated for differences in hospitalization risk. The analyzed covariates included age, gender, and socioeconomic 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 identified whether specific subpopulations were 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 the following: elevated night-time temperatures, duration of heat events, lag effects between exposure and total health impacts, and synoptic weather types. Studies have found that cooler night-time temperatures help minimize the daily effect of heat on mortality (37), that lengthier heat events increase health risks (8, 38), 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 (39, 40) and morbidity (41) rates on heat days.

The current 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:

$$\log\mu_j=\beta_0+\beta_2\text{difference}, \quad [5]$$

$$\log\mu_j=\beta_0+\beta_1\text{aboveThres}+\beta_2\text{difference}, \quad [6]$$

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:

$$\log \mu_j = \beta_0 + \beta_2 \text{duration}, \quad [7]$$

$$\log \mu_j = \beta_0 + \beta_1 \text{aboveThres} + \beta_2 \text{duration}, \quad [8]$$

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 (42):

$$E(Y_j) = \exp\{\alpha + f(h_{\sim j}) + \text{covariates} + s(\text{time})\}, f(h_{\sim j}) = \sum_{l=0}^{L} \beta_l h_{j-l}, \quad [9]$$

where Y_j is the hospital admission count on day *j*, *s*(time) is a spline curve over time, and $f(h_{\sim j})$ is a function of humidex values on days up to day *j*. This model takes a weighted effect of humidex on day *j* and the previous *L* days. Using different constraints or temporal structures for β_l, $l=0, ..., L$, allowed 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 (43).

Finally, we 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 (40, 44) and morbidity (41). Using daily spatial synoptic weather type classification data for the Seattle/Tacoma station (45), we explored effect modification by applying the same method used for individual-level characteristics.

Results

King County population and climate

King County, the largest county in the Pacific Northwest, is the 14th largest county in the US, and accounts for approximately 30% of the State's population throughout the study's time frame (23, 30). From 1990 to 2010 the county's population increased by 28%, with age groups 45–64, 65–84, and 85+ years increasing by 88%, 19% and 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 to September, comprising 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 six-fold, with no adjustment for inflation. Over 1990–2010, the average cost per day of stay was US$3388, whereas the average total cost for all of King County was approximately US$4 million per day. Table 2 provides descriptive demographic data by age and percent change in population from 1990 to 2010, as well as data on admission counts and costs from 1990 to 2010. Table 3 describes meteorologic 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 to 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 to 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 to September days. The average humidex on heat days was 38.7°C (101.7°F) (Table 3). Relative risk estimates and 95% confidence intervals (CI) 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 with 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 better understanding of the relative burden of hospitalization, the proportional morbidity is illustrated in Figure 1. Cause-of-admission categories run along the abscissa, whereas 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 following: 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 disorder estimate should be considered with caution, given the

Table 2 Descriptive data: population demographics, admission counts and costs for King County, Washington, 1990–2010.

Census population			
	1990[a]	2010[a] (% 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	$3389/day	$1072/day	$7328/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%)	
Socioeconomic status	Probable low SES[b]	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%)	

[a]Source: Washington State Department of Health. [b]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.

Meteorologic Data (1990–2010, May–Sept)	
Countywide 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%)
Countywide 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%)
Countywide maximum across all years	°C (°F)
Humidex	39.7°C (103.5°F)
Temperature	31.4°C (88.5°F)

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 better understanding of the relative burden of hospitalizations stratified by age and cause of admission, the proportional morbidity is illustrated in Figure 2, which shows 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, whereas 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 was J-shaped when estimated by continuous splines. The relationship illustrated an increased risk of morbidity from exposure to humidex

Table 4 Relative risk analysis results: Increased risk (95% CI) in hospital admissions on a 99th percentile (36.2°C) heat day compared with a non-heat day, by age group and cause of admission[a].

	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)**[b]	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							
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)**[c]	**2.42 (1.45, 4.06)**[d]	**3.42 (2.3, 5.08)**	**4.43 (2.99, 6.56)**

[a]Bolded relative risk values are significantly >1 ($p<0.05$); – indicates too few cases available to calculate. [b]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). [c]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). [d]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).

exceeding approximately 33°C humidex. A piecewise linear approximation was used to summarize the effect of heat 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 was 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 piecewise linear approximation for King County's unplanned, non-traumatic log-hospitalization rate and humidex relationship.

Intensity estimates and 95% CI for all age groups and categories of hospital admission are reported in Table 5. For all ages and all non-traumatic causes, we observed a 1.6% increase in hospitalizations per degree increase in average countywide 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 following: 15–44 age group, chronic obstructive pulmonary disease (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 was based on a small number of cases, as reported in Table 5.

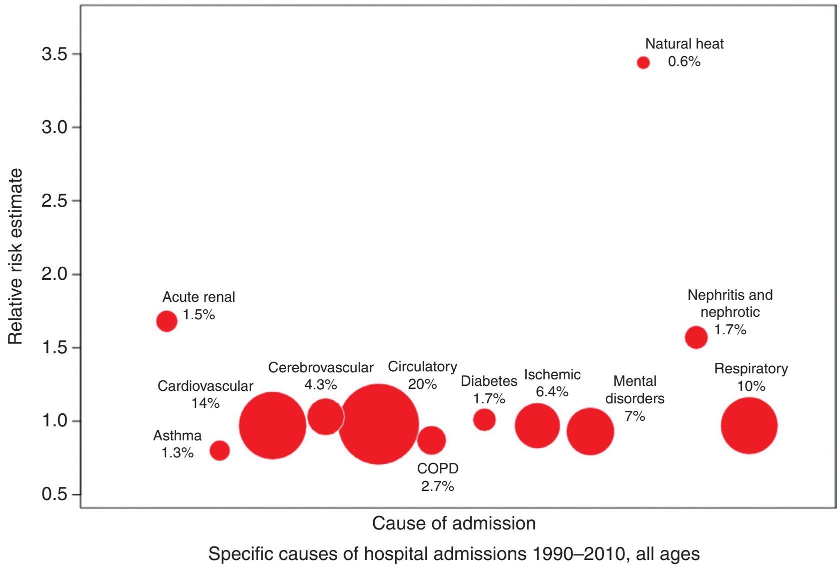

Figure 1 Proportional cause-of-hospitalization burden in relation to total morbidity, on 1% heat days.
Size of bubbles represent proportion of admissions compared with all non-traumatic admissions, whereas placement on the y-axis represents the relative risk estimate; statistically significant causes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

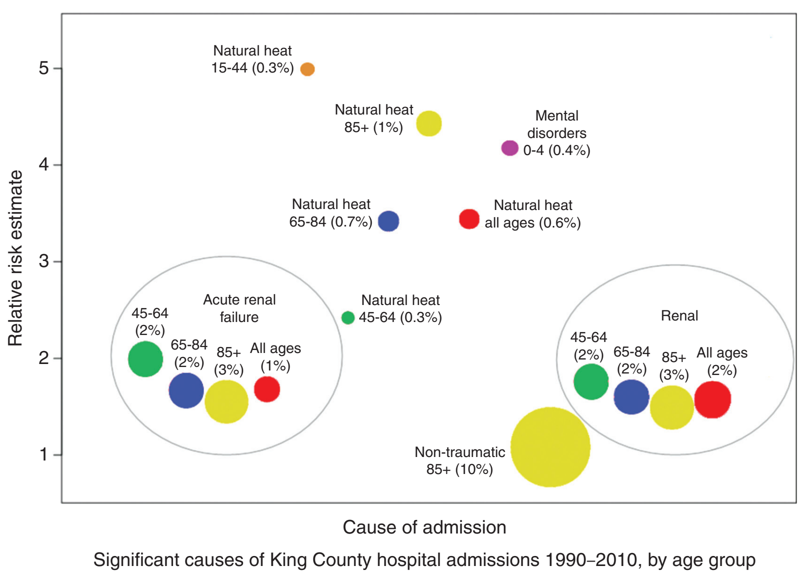

Figure 2 Proportional cause-of-hospitalization burden in relation to total admissions, on 1% heat days, by statistically significant age category.
Area of bubbles represent proportion of age-adjusted hospitalizations compared with non-traumatic causes, whereas placement on the y-axis represents hosptial admission relative risk estimate.

Effect modification with individual-level characteristics

We did not find that gender or socioeconomic 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.

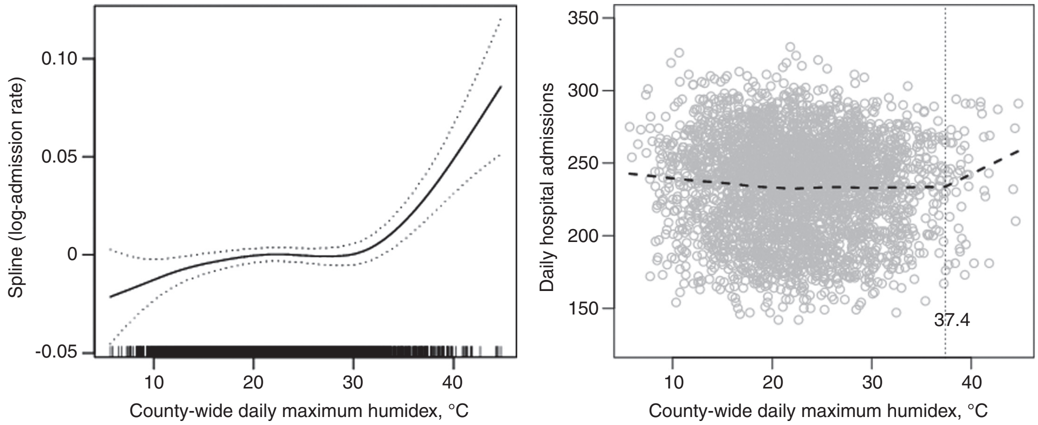

Figure 3 Nonparametric spline model of unplanned, non-traumatic log-hospital admission rate and humidex relationship. (Right) corresponding piecewise approximation using a natural spline below the optimal threshold and a linear piece above 37.4°C Humidex.

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. Finally, 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 because it 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 captured the overall contribution of heat to excess morbidity on heat days, whereas 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 by 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 with a non-heat wave day, whereas Kovats et al. (46) 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 (47) 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 based on 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 respiratory-related hospitalizations in all age groups. 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 to August 1, 2006 California heat wave as compared with a referent period. Li et al. (48) also found comparable time series estimates for endocrine (1.09%), genitourinary (1.12%), and renal failure (1.13%) causes of hospitalization, considering the results were per degree increase above a lower (29.5°C) threshold.

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[a].

	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%)
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%)**[b]

[a]Bolded time series estimates are significantly >0 (p<0.05); – indicates too few cases available to calculate; results have been rounded to 1 decimal place. [b]Although it is statistically significant, the estimate is based on a small number of cases (230 cases on non-heat days, 18 cases on a heat day).

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 suggested that hospitalizations affected 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 (33). With the time series analysis, our results also showed that heat affected the younger age groups (15–44, 45–64, and 65–84). This is contrary to what we have found with mortality (33), where heat intensity almost exclusively affected the 85+ age group. Similarly, Li et al. (48) 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 (33). Our mortality results, which showed increased circulatory (4.1%) and cardiovascular deaths (4.3%) with each degree increase in humidex above the threshold (36.0°C), paralleled the association we found between increased circulatory (4.8%) and cardiovascular hospitalizations (4.4%) per degree above threshold. It has been hypothesized in previous works that the time between heat exposure and resulting cardiovascular death is short (47), and that social isolation increases the risk of death (46, 47, 49). It has also been found that cardiovascular mortality observed on extreme heat days was higher for out-of-hospital deaths than in-hospital deaths (50). Our mortality (32) 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. Although our mortality (32) 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 with a non-heat day, with risk increasing 14.22% for each degree increase in humidex above 36.0°C.

Hansen et al. (27) 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 with non-heat wave days), whereas 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). Meanwhile, 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 like diabetes prevalence. However, with roughly 44% of new kidney-failure cases nationwide originating from diabetic patients (51), 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 future outreach and prevention programs (52).

Effect modification

Aside from age, this study did not find any indication that individual-level covariates of gender, admission source, admission type, and socioeconomic 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 (29), educational achievement, and social isolation affect risks for hospitalization and death (21, 50). An alternative explanation for the lack of identified vulnerable populations in this study could derive from the low prevalence of air conditioning in our region. Hamlet et al. (53) 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 (3, 21, 54). It is possible that our region's nearly universal lack of residential air conditioning is masking an otherwise observable vulnerable population.

Our 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 have been 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 et al. (55) noted that adjustment for air pollutants should be conducted with caution and clear rationale because controlling for non-confounders can lead to biased estimates of heat effects. Several studies have adjusted for air pollution (29, 46, 48) but lacked a sensitivity analysis comparing adjusted to unadjusted rates or estimates of effect modification. Green et al. (18) adjusted for ozone and $PM_{2.5}$ in their analysis of nine California counties, and observed slight decreases in hospitalization risks for all-respiratory diseases and pneumonia compared with unadjusted rates; however, they found 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 (5, 6, 56).

Limitations

The limitations of this study include possible exposure misclassification and inappropriate geographic boundary selection. Our study uses a daily county-wide averaged maximum humidex value to estimate heat exposure. Averaging across a large geographic 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 a maximum humidex value to each case based on the closest meteorologic grid center point to the hospital being 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 our model threshold may be higher than the true heat-health threshold by using the average daily relative humidity. 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 geographic unit of analysis may not accurately reflect the spatial variations in the effects of heat on hospitalization. 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. (29) who 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.

The current study did not correct for multiple comparisons. A Type 1 error may occur when numerous subgroups are analyzed for effect difference. The more comparisons 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 (e.g., Bonferroni) could be applied to our analyses (57). 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 in concurrence with existing literature and the 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 statistic methods. Our study is novel because 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. 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; 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 aimed to estimate the effect of heat on morbidity. The results, however, point to an incomplete estimation, where only the advancements of diseases serious enough to require hospitalization have been captured. Future works should estimate heat-health outcome relationships that precede hospitalization or are not serious enough to require admission. Future research is also needed to validate the methods used to model our heat-morbidity relationship, given that our piecewise 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 because improvements would affect both hospitalization admission and mortality rates. Finally, our findings warrant additional investigation into the role played by heat exposure 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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