Environmental Research 240 (2024) 117525

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

The association between climate and emergency department visits for renal and urinary disease in Charlottesville, Virginia

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A R T I C L E I N F O

Keywords:
Renal disease
Urinary disease
Climate
Emergency department admission
Generalized additive model
Distributed lag non-linear model

A B S T R A C T

Diseases of the kidney and urinary tract impose a significant portion of the total disease burden, and linkages to high temperature exposure suggest that this burden may increase in the near future. We examined the association between climate and daily emergency department (ED) visits for kidney and urinary disease at the University of Virginia main hospital in Charlottesville, Virginia from 2005 to 2020. Generalized additive models and distributed lag nonlinear models were used to examine these associations over a 21-day lag period. After testing a variety of weather variables from observations taken at the Charlottesville, Albemarle County Airport weather station, 1 p.m. temperature was found to have the strongest association with ED visits for renal and urinary visits while controlling for seasonal and trend factors, air quality, day of the week, and wintry weather.

The relative risk of ED visits exhibited a stronger association with high temperatures compared to low temperatures. The heat response was pronounced at short lags (0–1 days) with the relative risk (RR) increasing when 1 p.m. temperatures exceeded 20°C and peaking at 29°C (RR = 1.28). By comparison, low temperatures (≤0°C) exhibited a negative association (RR = 0.80 at −10°C) at short lags (0–1 day), with evidence of a weak RR increase at lags of 2–3 and 9–14 days.

These results for ED visitation are consistent with other studies linking high temperatures to acute kidney injury, chronic kidney disease, the development of kidney stones, and other associated illnesses. A better understanding of the impact of temperature extremes in generating or exacerbating existing conditions could assist medical health professionals in the prevention and management of these diseases during extreme weather events.

1. Introduction

Increases in mean global temperatures, including those linked to human-induced climate change, have heightened awareness of how temperature extremes can impact human health. In the United States, chronic kidney disease (CKD) impacts about 15% of the adult population, and the prevalence of end-stage renal disease is among the highest in the world (Johansen et al., 2021). A growing body of evidence finds associations between atmospheric conditions and kidney disease (Barraclough et al., 2017; Borg et al., 2017; Ephraim et al., 2020; Hansen et al., 2008; He et al., 2022; Kovats, 2004; Liu et al., 2021; McTavish et al., 2018; Ostro et al., 2010; Tseng et al., 2020). The association between weather and climate extremes and kidney and urinary disease varies regionally, and understanding impacts at a local level is important for the proper prevention and management of patients (Barriopedro et al., 2011; Blashki et al., 2011; Lee et al., 2019). However, relatively few studies have investigated the association between climate and renal and urinary emergency department (ED) visits (Hajat et al., 2010; Knowlton et al., 2009; Ostro et al., 2011; Turner et al., 2012).

Prior research has linked temperature to renal/urinary health, with extreme temperatures coupled to increased admission rates and higher case counts for a variety of related renal and urinary diseases and conditions (Semenza et al., 1999; Tseng et al., 2020). High temperatures in particular are associated with increased morbidity and mortality, especially among women and the elderly, with evidence of differences coupled to age, race/ethnicity, and socio-economic status (Al-Badr and Al-Shaikh, 2013; Chu et al., 2022; Fletcher et al., 2012; He et al., 2022; Kovats, 2004; Liu et al., 2021; Rowe and Juthani-Mehta., 2013; Simmering et al., 2021; Wen et al., 2022). Physiological associations include dehydration and electrolyte imbalance (Bouchama and Knochel, 2002; Kovats, 2004; Satirapoj et al., 2016; Wen et al., 2022), decreased filtration (Chu et al., 2022; Dally et al., 2018; García-Trabanino et al., 2015; Johnson et al., 2019; Kim et al., 2018; Tseng et al., 2020), inflammation and the formation of blood clots (Dally et al., 2018; Hart et al., 1982; McTavish et al., 2018; Zager and Altschuld, 1986) and

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https://doi.org/10.1016/j.envres.2023.117525
Received 16 June 2023; Received in revised form 19 October 2023; Accepted 25 October 2023
Available online 28 October 2023
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Abbreviations

AKI	acute kidney injury
CKD	chronic kidney disease
DLNM	distributed lag nonlinear model
ED	emergency department
EST	Eastern Standard Time
GAM	generalized additive model
ICD	International Classification of Disease
IRB	Institutional Review Board
NWS	National Weather Service
RR	relative risk
UTI	urinary tract infection
UVA	University of Virginia

development of renal calculi (Bobb et al., 2014; Borghi et al., 1993; Fletcher et al., 2012; Moyce et al., 2017). Low temperatures subject the body to a homeostatic threat by decreasing the body's immune function and subjecting individuals to seasonal diseases, such as the cold or flu. Individuals with CKD are at higher risk of developing complications (LaVoy et al., 2011). The kidney also is subject to damage at low-temperature exposure from an increased burden on the glomeruli due to hypovolemia, increased incidence of atrial dysrhythmias, and diuresis (Sun, 2010).

In this retrospective study, we utilize a long time series of daily ED visits from the University of Virginia (UVA) Hospital in Charlottesville, Virginia to investigate the association between renal and urinary disease and climate.

2. Materials and methods

2.1. Study setting and data

Charlottesville is a mid-sized city in the central Virginia piedmont about 200 km southwest of Washington, D.C. The city and surrounding county have a population (in 2023) of about 150,000 residents. The climate is humid subtropical, with warm and humid summers and cool but not cold winters. Precipitation is evenly distributed throughout the year with no demonstrable dry season. UVA Health is the largest of the two primary hospitals that serve residents of Charlottesville and the surrounding counties.

Daily counts of ED visits for renal and urinary diseases were acquired for the UVA main hospital in Charlottesville, Virginia. UVA Health, which serves the city of Charlottesville and surrounding regions, receives an average of 65,000 ED visits annually and serves a large patient population. All study subjects were patients who visited the UVA Medical Center ED between January 1, 2005 and December 31, 2022. Daily total ED visits for renal and urinary diseases were counted following the discharge diagnosis codes from the International Classification of Disease 9th (ICD-9) and 10th (ICD-10) revisions (Table S1). There was an average of 5.53 genitourinary ED visits per day over the 18-year period, and the time series is relatively continuous, with no obvious abnormalities associated with the ICD-9 to ICD-10 changeover that took place on October 1, 2015 (Fig. 1). The most inconsistent aspect of the record is the period of relatively high daily visits observed from 2006 to 2009. This work was evaluated and approved by the UVA Health System's Institutional Review Board (HSR# 24496).

The study population's average age was almost 50 years, but the standard deviation is large (24 years) (Table 1). Females accounted for a much higher percentage of visitations than males, and whites accounted for almost 70% of the total. Patients treated were older and more likely to be Black or female compared to the overall population in the region. Over one-third of ED patients were subsequently admitted to the hospital (Table 1).

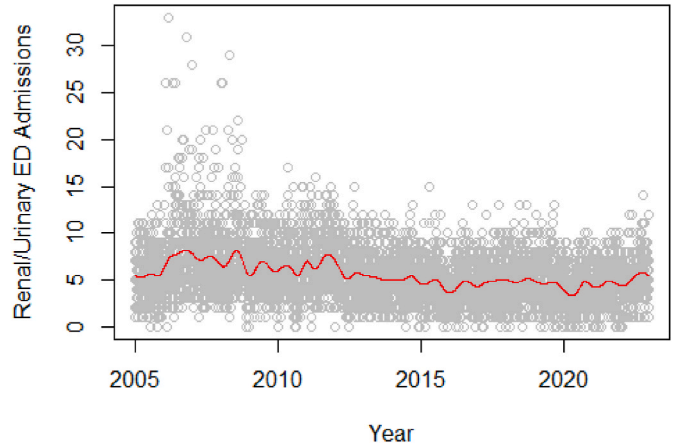

Fig. 1. Daily frequency of emergency department visits for renal/urinary diseases to the University of Virginia Medical Center from January 1, 2005 through December 31, 2022. The red line is a cubic regression spline fit using 4 degrees of freedom per year.

Table 1
Summary demographic statistics for the study population.

	UVA Health	Charlottesville[b]	Albemarle
AGE (years)			
Mean	49.5	42.5	42.5
Standard Deviation	24.2		
GENDER (%)			
Female	64.9	51.6	51.9
Male	35.0	48.4	48.1
RACE (%)			
Black	23.8	19.9	10.6
White	69.0	71.5	83.5
Other	7.2	8.6	5.9
ED DISPOSITION[a] (%)			
Admitted	36.5		
Discharged	62.3		
PAYOR[a] (%)			
Medicare	21.6		
Medicaid	44.4		
Private	23.6		

[a] based on data from July 1, 2017 through December 21, 2022 only.
[b] In Virginia, cities are independent of the counties in which they reside, so the Albemarle County data do not include data for the city of Charlottesville proper.

2.2. Weather data

Weather data were acquired from U.S. National Weather Service (NWS) archives from measurements taken at the first-order weather station located at the Charlottesville-Albemarle County airport (station code: CHO) and downloaded from a website (https://mesonet.agron.iastate.edu/request/download.phtml?network=VA_ASOS). These observations were collected and archived using standardized procedures established through the NWS Automated Surface Observing System. Weather measurements were taken using a standard data collection protocol established to provide essential operational weather observations for the Federal Aviation Administration and the Department of Defense, which includes routine quality control procedures. In this study, weather observations were acquired for 1 a.m., 7 a.m., 1 p.m., and 7 p.m. eastern standard time (EST). Any single missing observation was linearly interpolated from the two immediately adjacent times; otherwise, the day was assigned as missing.

To examine possible confounding effects of air quality, we acquired concentrations of ozone and particulate matter with diameters 2.5 μm or smaller ($PM_{2.5}$) from Environmental Protection Agency sources (https

://www.epa.gov/outdoor-air-quality-data/download-daily-data). These observations were taken at Albemarle High School, which is 7.5 km south of CHO and is in a more urbanized area than the neighborhoods surrounding the airport. We utilized daily mean values for each species.

2.3. Statistical models

A generalized additive model (GAM) approach was used to examine the relationship between weather and renal/urinary disease. Potential predictor variables were fitted with a smoothing spline to account for temporal variability (Fig. 1). Continuous and categorical predictor variables were added/removed from the model in a manner like that of fitting multiple regression models. The GAM in this study was utilized to examine the cumulative relationship between the predictors and the response (ED visits) over a 21-day lag (i.e., day of a given weather event and subsequent 3 weeks). Although there is no specific guideline regarding lag period length, this lag is consistent with prior research (Tasian et al., 2014) with the goal of being sufficiently long to account for disease latency, although some similar studies used shorter lag periods (e.g., Kim et al., 2018; Lim et al., 2018; Lin et al., 2013). We examined lagged effects on specific lag days using a distributed lag non-linear model (DLNM), which accounted for the simultaneous and lagged effects between each day's weather and the dependent variable (Gasparrini, 2011). The incorporation of GAM and DLNM approaches is a commonly used analytical strategy in environmental epidemiology (e.g., Chen et al., 2013; Davis et al., 2022; Guo et al., 2016; Lee et al., 2018; Liu et al., 2013).

A variety of potential weather predictors, including temperature, humidity, pressure, and numerous derived biometeorological indices, at different times of the day, were tested in the model, as were variable degrees of freedom in each spline term. The adjusted R-squared value, deviance explained, and generalized cross-validation score were used to compare models. The final model was:

$$\log(Y_t) = a + S(T1pm, 3) + S(trend, 18x3) + bPM_{2.5}(3) + cDOW + dWinterWeather,$$

where "Y" is the daily ED visit count, "t" is time, "a" is the y-intercept, "S" is a natural cubic spline with 3 degrees of freedom used to fit 1 p.m. temperature, and "trend" is used to fit temporal changes in the response, with 3 degrees of freedom applied in each of the 18 years of data to account for inter- and intra-annual variability in ED visits. "$PM_{2.5}$″ is the concentration of particulate matter with diameters of 2.5 μm or less, fitted with 3 degrees of freedom. Ozone was not included in the final model as it had no impact on the results. "DOW" is a categorical variable to account for day of week. Finally, “WinterWeather” is a binary variable that accounts for snow, sleet, ice, etc., based on the presence of sleet or ice and/or at least two inches of snow on a given day. This variable was added based on observations that people are reluctant to seek medical attention on days with wintry weather (Bhattacharyya and Millham, 2001; Giamello et al., 2022; Lee et al., 2016; Villeneuve et al., 2005). The "b,c,d" terms are estimated coefficient vectors. A Poisson link function was used to associate the predictors and outcome variables, and overdispersion in the count (ED) data was tested for in our model using the function from the "qcc" library in R Studio.

A DLNM was used to examine the simultaneous and lagged relationships between 1 p.m. temperature and ED visits for renal and urinary disease. This model used natural cubic splines with three equally spaced knots per year. The lag was run 21 days from the day of the weather event. The relative risk (RR) estimates were centered on the median 1 p.m. temperature value. The GAM and DLNM models were developed using the "mgcv" and "dlnm" libraries in R Studio, Version 2022.07.2.

3. Results

The plot of the ED visits over time from 2005 to 2022 shows evidence of both intra- and inter-annual variability (Fig. 1). A one-way analysis of variance factored on month indicates that there is a statistically significant difference in the monthly mean rates ($F = 3.667$, $p < 0.001$) with the highest visits in the summer months and lowest visits in fall and early winter. Yearly mean rates are even more varied ($F = 597.6$, $p < 0.001$) with the highest ED visits occurring from 2005 to 2010, driven by the numerous days with very high visits counts in this time period. There is also a strong day-of-week artifact with lower ED visits observed on Saturday and Sunday ($F = 12.81$, $p < 0.001$). Our primary climate predictor variable, 1 p.m. air temperature, demonstrates the expected seasonality for a midlatitude continental location like Charlottesville but no evidence of a trend over this period of record (Fig. 2, Table 2, Table S2).

Results from the GAM demonstrate a net impact of high temperatures on ED visits summed over a 21-day lag period (Fig. 3). As 1 p.m. temperatures increase from 20°C to 29°C, the RR of renal ED visits increases by 28%. Elevated risks remain evident at higher temperatures, but the RR peak is at 29°C. In contrast, ED visit risk declines as 1 p.m. temperatures drop below 18°C.

A DLNM was used to explore the lagged RR relationship in more detail (Fig. 4). At short lags of 0–1 day, the estimated RR of ED visits begins to increase when 1 p.m. temperatures exceed 20°C, with a maximum risk observed for temperatures above 32°C. Although there are some rather weak heat effects at longer lags, the greatest risk of ED admission is at short lags. Conversely, low temperatures exhibit negative risk at short lags, with RR as low as 0.80 on the coldest afternoons (1 p.m. temperature ≤ −5°C). However, there is a slight increase in risk 1–3 days later, with RRs exceeding 1.05.

The lagged estimates of RR are shown in more detail for five specific reference temperatures in Fig. 5. The lagged response at −10°C (0.02 percentile of 1 p.m. air temperature) exhibits a negative association at low temperatures, but an increase in ED visits that peak 2–3 days later. This is followed by a secondary decrease in RR for admission at days 3–7 (Fig. 5a). There is an immediate decrease in the RR of 15% at −5°C (1st percentile). There is little effect at 20°C (approximately the median temperature, Fig. 5c). For short lags, there is an increase in RR of 5% at 30°C (91st percentile) (Fig. 5d) and an even higher increase of 7% at 35°C (97th percentile) (Fig. 5e) in association with the warmest summer afternoons.

4. Discussion

In Charlottesville, Virginia, after adjusting for $PM_{2.5}$, day of the week, and winter weather, we found that the RR of ED visits for renal

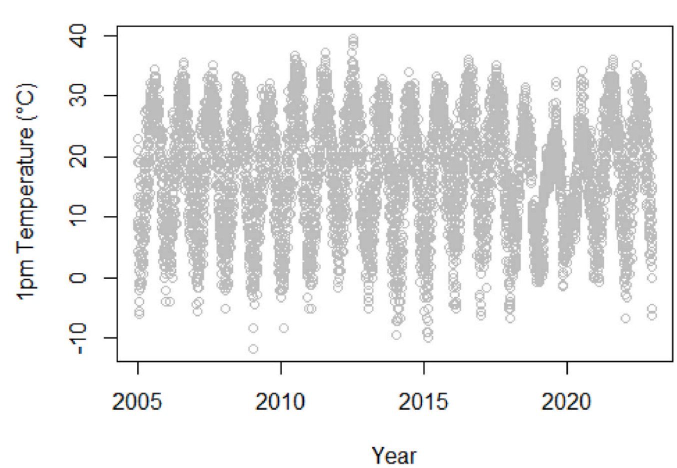

Fig. 2. Daily 1 p.m. air temperature (°C) from 2005 to 2022.

Table 2
Monthly summary statistics of 1 p.m. temperature (°C), including mean and median, minimum and maximum, and 1st and 3rd quartile values.

Month	Min Temp	1st Quartile	Median Temp	Mean Temp	3rd Quartile	Max Temp
Jan	−11.7	1.7	5.6	5.8	9.4	22.8
Feb	−10.0	2.8	6.7	7.2	11.1	25.0
Mar	−6.7	6.7	11.1	11.6	16.1	27.2
Apr	2.2	12.8	16.7	17.1	21.1	31.1
May	9.0	17.3	21.1	21.4	25.6	33.9
Jun	14.0	23.3	26.1	26.4	29.4	37.2
Jul	17.2	25.6	28.9	28.5	31.1	39.4
Aug	16.7	24.9	27.2	27.4	30.0	36.0
Sep	14.0	20.6	23.9	23.8	27.2	35.0
Oct	5.0	14.9	18.4	18.3	21.7	31.7
Nov	−1.3	8.3	12.2	12.8	17.2	27.8
Dec	−6.1	4.4	7.8	8.0	11.4	23.9

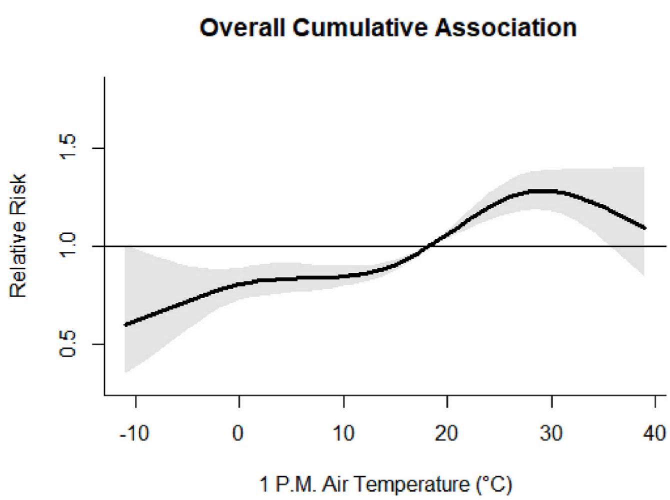

Fig. 3. Estimated relative risk of ED visits over a 21-day period as a function of 1 p.m. air temperature. The model controls for $PM_{2.5}$ concentration, day of week, and winter weather events. The curve is centered on the median temperature of 18.3°C. Gray shading shows 95% confidence intervals.

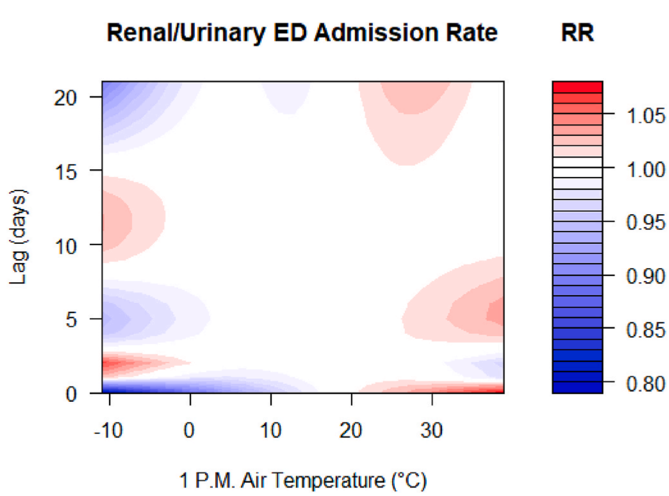

Fig. 4. Estimated relative risk of ED visits as a function of 1 p.m. air temperature and lag.

and urinary disease increased for both very high and very low temperatures. The coldest days (1 p.m. temperature <0°C) demonstrated a negative association with an RR of 0.80 over a 21-day period. The response to high temperatures is greater, with RRs approaching 1.30, whereas low temperatures have a peak RR reaching 1.06 about 2–3 days after the extremely cold day (1 p.m. temperature ≤ -10°C). ED visits begin to rise when 1 p.m. temperatures exceed 20°C, with the peak RR observed around 29°C. All of the heat-related lags are short, with ED visits increasing on the day of or the day after each heat event.

These results are generally consistent with previous studies (Fletcher et al., 2012; Kim et al., 2018; Lim et al., 2018; Liu et al., 2021; Wen et al., 2022). Research in the United States has linked extreme heat exposure to increased odds of hospitalization for renal failure in Taiwan (Lin et al., 2013). An analysis of heat waves on ED visits in Atlanta also found an increase in the RR for admission of renal disease of almost 10% at a lag of zero days (Chen et al., 2017), a result that is similar to our findings. In Australia, renal disease admissions increase by more than 10% during heat waves, primarily from acute kidney injury (AKI, Hansen et al., 2008; Nitschke et al., 2007). High temperature exposure subjects humans to a homeostatic threat, inducing the kidney to make thermoregulatory, physiological, and circulatory adjustments to maintain the normal physiological state (Lin et al., 2013).

Hot weather has been associated with renal function decline and an increased risk of hospitalizations and mortality from renal disease (Liu et al., 2021; Wen et al., 2022), especially in individuals with more advanced stages of CKD (He et al., 2022). Dialysis patients face a higher risk of complications from heat exposure (Kovats, 2004). Excessive sweating and resulting dehydration and electrolyte loss (Bouchama and Knochel, 2002; Satirapoj et al., 2016) may exacerbate kidney disease symptoms (Kovats, 2004; Wen et al., 2022), an issue that is particularly problematic among the elderly (Chu et al., 2022; Flynn et al., 2005; Kovats and Hajat, 2008; Lin et al., 2013; McTavish et al., 2018; Semenza, 1999; Tan et al., 1995; Varghese et al., 2005). Heat-related reductions in the glomerular filtration rate can lead to toxin accumulations in the body (Chu et al., 2022; Dally et al., 2018; García-Trabanino et al., 2015; Johnson et al., 2019; Kim et al., 2018; Tseng et al., 2020).

Kidney stone formation has also been associated with exposure to high temperatures. When individuals sweat, they lose extracellular fluid, increasing vasopressin and thus water reabsorption to maintain fluid homeotic balance, but this increase in water absorption decreases urine volume and increases uric acid concentration and osmolarity, causing the formation of kidney stones from the supersaturation of uric acid and calcium (Borg et al., 2017). Some studies have found an increase in morbidity for urolithiasis during summer period with high temperatures (Al-Tawheed et al., 2003; Lo et al., 2010; Luján et al., 2011). Heat stress and dehydration subject individuals to low urine and increased uric acid, increasing the risk of developing renal calculi (Borghi et al., 1993). There is an increased prevalence of kidney stones in populations exposed to extreme heat, especially in minority populations with lower socioeconomic status (Bobb et al., 2014; Fletcher et al., 2012; Moyce et al., 2017). Kidney stone admissions increase in metropolitan communities in the United States with higher daily mean temperatures. The relative risk of urolithiasis morbidity for a daily mean temperature of 30°C (compared to 10°C) exceeded 1.35 in Dallas, Atlanta, Chicago, Los Angeles, and Philadelphia (Tasian et al., 2014). The fraction of the U.S. population living in high-risk zones for nephrolithiasis is projected to increase 56% by 2050 with the northward expansion of the southeastern U.S. kidney stone belt (Brikowski et al., 2008).

Exposure to high temperatures, including exertional heat strokes, have also been associated with morbidity from AKI. Hyperuricemia and nephritis are common acute responses to heat stroke (Hart et al., 1982; Zager and Altschuld, 1986), and the oxidative stress and inflammation caused by heat exposure can further exacerbate kidney injury (Dally et al., 2018; McTavish et al., 2018). Heat stress can increase blood viscosity, leading to the formation of blood clots, which can block blood flow to the kidneys and other organs, causing damage (McTavish et al., 2018). A study conducted in Thailand found that patients who experienced exertional heatstroke reported AKI with hyponatremia, hypokalemia, hypophosphatemia, hypocalcemia, and hypomagnesemia (Satirapoj et al., 2016).

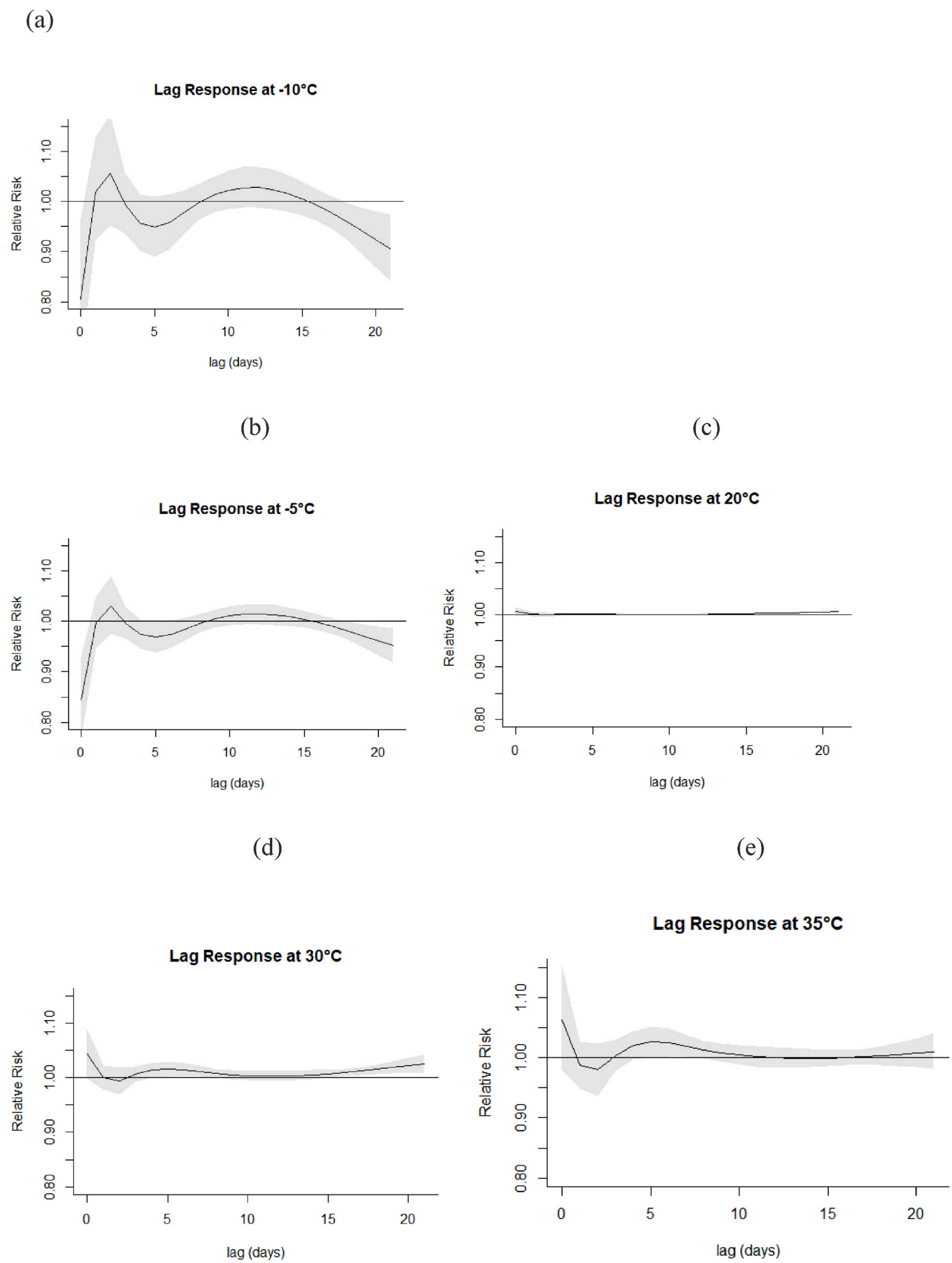

Fig. 5. Relative risk of ED visitation for renal/urinary disease as a function of lag for days with a 1 p.m. temperature of −10°C (a), −5°C (b), 20°C (c), 30°C (d), and 35°C (e). Gray shading indicates 95% confidence intervals. All plots are referenced to the median 1 p.m. air temperature of 18.3°C.

Low temperatures are associated with a decline in ED visit risk on the day of the event but show a lagged increase in RR 2–4 days later. Sun (2010) found that the highest proportion of CKD was attributed to hypertension and diabetes mellitus, both of which are risk factors for CKD (Kazancioğlu, 2013). It could also be possible that individuals, including those of lower socioeconomic status who rely on public transportation, may choose to avoid traveling to the ED on days with very low temperatures (Bhattacharyya and Millham, 2001; Giamello et al., 2022; Lee et al., 2016; Villeneuve et al., 2005).

4.1. Limitations

First, because of the study design, the associations between climate and renal/urinary morbidity do not indicate a causative link. However, the associations inferred herein do tend to corroborate other research that suggests a causal relationship. Second, the results for this population of primarily central Virginia residents may not be applicable to other groups owing to differences in genetic and demographic profiles and adaptation to local climate variations. Third, the specific exposure profile of individual patients that could have induced admission to the ED is unknown. Given our use of a single weather station to represent the region, the spatial temperature variability is a source of error. But some research suggests that this error may not be that large or significant (Guo et al., 2013). Likewise, we do not know the spatial distribution of the study patients, but assume that most of them live and work in the immediate area. However, the relatively long ED visit time period provides greater confidence that the relationships found in this study are real and not arising from random chance. Fourth, the lagged response of each individual to some precipitating event, such as a warm day, will vary, and this is a source of error that we attempt to account for with the DLNM. Finally, Charlottesville and environs are a relatively small metropolitan area; thus, daily ED visit counts are small and subject to high daily variability. The small sample size makes it difficult to develop models for subcategories (such as specific renal/urinary diseases) to allow for direct comparisons with studies from much larger metropolitan areas. Likewise, combining renal diseases with urinary tract diseases implies that the physiological response to environmental conditions is similar. This may not be correct, and future research conducted for locations with much larger daily sample sizes is warranted to identify the biophysical mechanisms through which climate factors might exacerbate these morbidities.

5. Conclusions

In Charlottesville, Virginia, ED visits for renal and urinary diseases are associated with both low and high temperatures, with the heat effects stronger than the cold effects. Days with low temperatures are associated with reduced ED visits, but there is a lagged effect evident starting 2 days after the cold event, resulting in increased ED visits. Heat impacts demonstrated a more immediate, significant increase in ED visits the day of the heat event with a secondary lagged peak occurring 4–7 days post-event. Exposure to extreme heat can increase the RR of ED admission by 28%.

With humans facing increasing heat exposures from climate change and urban heat islands, coupled with the prevalence of renal and urinary disease, understanding the environmental factors that influence acute rates of morbidity is crucial. The research presented here is generally consistent with other studies emphasizing an important association between high temperatures and renal/urinary diseases. More work needs to be done on the physiological linkages between high temperature exposure and specific disease outcomes. By comparison, less is understood about connections between renal and urinary diseases and cold extremes. The ability to use meteorological data to inform the public and prepare healthcare professionals for the prevention and management of disease could be a useful tool for patient care and hospital management. Since some of the impacts of weather are behaviorally based, increased public awareness during cold and hot events could be beneficial for the protection of at-risk patients with kidney and urinary diseases.

Author contributions

Jesus S. Neyra: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Visualization. Robert Davis: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data access is governed by the UVA IRB Data Management and Secutiry Plan. A statement regarding data access is included with the manuscript.

Acknowledgement

We thank Prof. Wendy Novicoff (UVA) for her assistance in culling the ED visit data utilized in this research and in garnering IRB project approvals. We also thank four anonymous referees for their careful evaluation of our initial manuscript, which was improved substantially from their feedback.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2023.117525.

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