BMC Public Health

RESEARCH Open Access

Association between heatwave exposure and rapid kidney function decline: a longitudinal cohort study from CHARLS

Jinshi Zhang[1†], Binqi Wang[1†], Binxian Ye[1], Bin Zhu[1*] and Yueming Liu[1*]

Abstract

Background and hypothesis The worldwide prevalence of renal disease is substantial, with a significant impact on public health and the economy due to the high rates of mortality and morbidity associated with this condition. It is anticipated that projected rises in temperature in a warm climate will have a significant impact on kidney health, with older adults potentially experiencing the most pronounced effects.

Methods In the China Health and Retirement Longitudinal Study, we assessed daily heatwave exposure individually for 6450 participants and kidney function decline during follow-up from 2011 to 2015. Kidney function, assessed by estimated glomerular filtration rate (eGFR), were tested at the baseline and endpoint surveys. 12 heatwave definitions combining four thresholds and three durations were used. The investigation used the number of heat wave days from 2011 to 2015 as a metric for heat wave exposure according to each of the previously specified criteria of a heat wave. Rapid kidney function decline was defined as a decrease in eGFR $\geq$ 3mL/min/1.73 m^2/year. Multivariate logistic regression models was employed to evaluate the association between heat wave and the risk of rapid eGFR decline.

Results The results showed that the rise in middle to high-intensity heat wave events was connected with a significant risk of rapid kidney function decline. Moreover, we confirmed that the connections between heat wave and rapid kidney function decline were robust after further adjustment of age, gender, medical history, drinking status, smoking status, and biochemical.We observed that males, urban residents, and smoked or drank alcohol were identified as vulnerable populations.

Conclusion This study found that increased heatwave exposure was associated with a higher risk of rapid kidney function decline in older adults.

Keywords Heatwave, Kidney function decline, Elderly, Environmental health

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Introduction

Approximately 9.1% of people worldwide have chronic renal disorder, which is described as a progressive deterioration in renal function. Causes include diabetes, glomerulonephritis, and inherited disorders [1]. The worldwide prevalence of renal disease is substantial, with a significant impact on public health and the economy due to the high rates of mortality and morbidity associated with this condition [1, 2]. It is therefore recommended that global public health initiatives accord a higher priority to the protection of kidney function in high-risk groups [3].

The rising worldwide temperatures need focused consideration of the possible health hazards related to the renal system [4]. In addition to its function in thermoregulation and the prevention of dehydration during periods of elevated temperature, the kidney is a principal organ in the development of heat-related diseases [5]. Furthermore, the aforementioned impaired responses may contribute to the exacerbation of the decline in estimated glomerular filtration rate (eGFR) or the elevation in albuminuria (or both) in the absence of clinical pyrexia. Occupational health studies indicate that consistent, intense physical exertion in hot conditions, without sufficient rest and rehydration, can reduce the function of the kidneys and potentially cause acute and chronic renal disorders in workers [6]. It has been proposed that the combination of high climatic and physiological heat stress is the principal cause of Mesoamerican nephropathy, along with various types of chronic renal impairment of indeterminate origin. Some researchers have suggested that this phenomenon be termed climate-change nephropathy [7]. Many of the hottest places globally are projected to have a high incidence of chronic kidney disorders [8]. A number of epidemiological investigations have revealed a consistent and positive correlation between heat exposure and an elevated risk of morbidity and mortality connected with kidney [9–14].

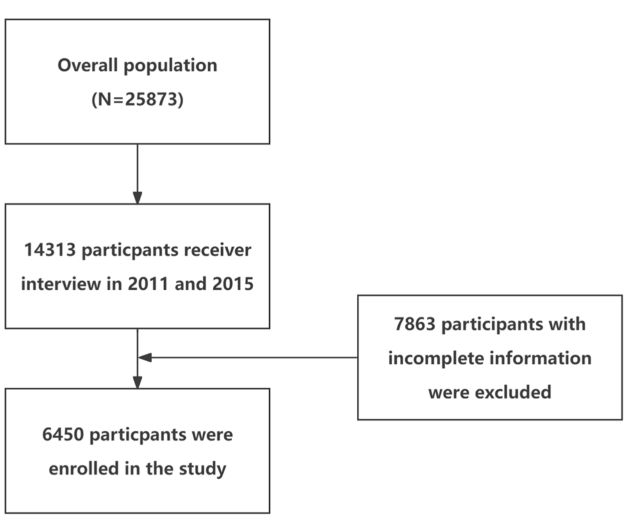

Fig. 1 Flowchart illustrating participant inclusion criteria

Nonetheless, to this day, little empirical proof exists, save from short-term occupational investigations performed in Central America [15], that heat exposure is connected with a rapid decline in renal function. This investigation aimed to examine the longitudinal relationship between heat waves and the risk of rapid deterioration of renal function. The information utilized in this investigation was sourced from the China Health and Retirement Longitudinal Study (CHARLS).

Materials and methods

Study design and study population

This research utilized data from CHARLS, a large-scale national survey targeting individuals aged 45 and above. The survey covers 150 counties or districts and 450 villages or residential committees across 28 provinces throughout mainland China. The initial data collection, referred to as Wave 1, was conducted in 2011–2012, with follow-up surveys completed in 2013, 2015, and 2018, designated as Waves 2, 3, and 4, respectively. All participants were mandated to engage in an in-person interview and complete a standardized questionnaire biennially. A comprehensive account of the CHARLS project has been presented in a previous publication [16].

It should be noted, however, that only the 2011 (Wave 1) and 2015 (Wave 3) surveys collected blood samples. Accordingly, the two waves were employed in the construction of the longitudinal cohort. The selection criteria for this study were: (1) older adults aged 60 years or younger; (2) participants interviewed in 2011 and 2015 (Waves 1 and 3); and (3) availability of serum creatinine data and key independent variables.

Figure 1 provides a detailed flowchart illustrating the study design. The analysis involved 6,450 individuals who participated in the 2011 and 2015 survey waves. The sample size of 6,450 participants was determined based on the availability of serum creatinine data from the 2011 and 2015 CHARLS waves. This sample size provides sufficient statistical power to detect meaningful associations between heatwave exposure and rapid kidney function decline, given the longitudinal nature of the study and the inclusion of multiple covariates in the analysis. Additionally, the large geographical coverage of CHARLS ensures a diverse population, enhancing the generalizability of the findings.

Due to the unavailability of precise home addresses, environmental exposure was assessed solely at the city level of residence. Residential stability was verified through three mechanisms: (1) Multi-wave geolocation consistency using China's standardized administrative coding system (county-township-village levels) with GPS coordinates from in-person interviews; (2) Field verification by survey teams cross-referencing local records and satellite imagery; (3) Participant confirmation of address changes through embedded questionnaire items. The underlying hypothesis suggested that participants living in the same urban area would experience comparable exposure levels. Additionally, it was presupposed that the participants' residential locations were still relatively stable. This approach aligns with CHARLS's geolocation protocols and China's residential patterns where 94.1% of over-60s maintain decade-long residence stability (National Bureau of Statistics, 2020).

All participants provided informed consent, and the research methodology received approval from the Ethical Review Committee of Peking University (approval number: IRB00001052-11015).

The dataset employed in this investigation is freely accessible.

Assessment of rapid kidney function decline

Kidney function assessment was conducted by calculating eGFR, which was detected by employing the Chronic Kidney Disease Epidemiology Collaboration (CKD-EPI) creatinine equation [17]. The eGFR obtained from participants in 2011 and 2015 served as measures of renal function at the starting point and endpoint, respectively. A decline in renal function was identified as rapid if the eGFR decreased by a minimum of 3 ml/min/1.73 m^2 per year, a validated threshold supported by international consensus guidelines and population studies demonstrating clinical relevance in CKD progression [18–20].

Assessment of heat wave

Our data is sourced from RESDC (Resource and Environment Science Data Center of the Chinese Academy of Sciences), which is an authoritative platform for sharing scientific data in the field of resources and environment. The platform primarily serves the needs of scientific research, policy-making, and the general public. The data originates from over 2,400 meteorological stations across China and mainly includes daily observational data on variables such as air pressure, temperature, precipitation, evaporation, relative humidity, wind direction and speed, sunshine duration, and ground temperature at 0 cm. The temperature data is further divided into the following ten components: 1 StationId: Station Code, 2 Lat: Latitude (degrees), 3 Lon: Longitude (degrees), 4 Alti: Altitude of the observation field (meters; if the station altitude is an estimated value, 10,000 is added to the estimate), 5 Year: Year, 6 Mon: Month, 7 Day: Day, 8 TEM_Avg: Average Temperature (°C), 9 TEM_Max: Daily Maximum Temperature (°C), 10 TEM_Min: Daily Minimum Temperature (°C) [21]. Previously, there has been a paucity of consistency in the definitions of heat waves employed in surveys. The majority of surveys employed a variety of temperature thresholds and the number of consecutive days as criteria for defining a heat wave. In this study, a heat wave is defined by daily average temperature. Based on local acclimation and climate data, we established city-specific thresholds at the 90th, 92.5th, 95th, and 97.5th percentiles for daily mean temperature. These thresholds were used to categorize heat wave durations as follows: ≥ 2 days, ≥ 3 days, and ≥4 days, resulting in twelve unique definitions of heat waves (Table 1) [22, 23]. The investigation used the number of heat wave days from 2011 to 2015 as a metric for heat wave exposure according to each of the previously specified criteria of a heat wave.

Covariates

The investigation gathered baseline features of participants during the initial visit in 2011, encompassing variables such as sex, age, marital status, and place of residence. Furthermore, data were collected on participants' lifestyle behaviors, specifically their smoking and alcohol consumption statuses. Health-related variables were also incorporated, including self-reported chronic disorders such as diabetes, cardiac disorder, stroke, and hypertension, as well as the assessment of activities of daily living (ADL).

Statistical analysis

All statistical analyses were performed following a three-phase approach. First, we conducted descriptive analyses for baseline characteristics: continuous variables with normal distribution (assessed by Kolmogorov-Smirnov test) were presented as mean ± standard deviation with 95% confidence intervals (calculated as Mean ± 1.96 × SD/n), and compared using Student's t-test or ANOVA, while non-normally distributed variables were expressed as median (interquartile range) with bootstrapped CIs (1,000 resamples) and analyzed using Mann-Whitney U or Kruskal-Wallis tests. Categorical variables were reported as frequencies (%) with Wilson score intervals and compared via χ^2 test.

Second, we employed multivariable logistic regression models to examine the association between heatwave exposure (independent variable) and rapid kidney function decline (dependent variable, defined as eGFR decline ≥ 3 mL/min/1.73 m^2/year), adjusting for covariates in three sequential models: Model 1 (unadjusted), Model 2 (adjusted for demographic factors: age, gender, residence), and Model 3 (fully adjusted with additional clinical variables: stroke, heart disease, kidney disease, hypertension, diabetes, smoking/drinking status, and biochemical markers).

Finally, we performed stratified analyses by sex, age, residence, and lifestyle factors, incorporating interaction terms in the regression models to test subgroup

Table 1 Descriptive analysis for twelve types of heatwaves definitions in the present study

Heatwave definitions	Threshold percentile (°C) for temperature	Duration (Day)	Intensity categories
WMO_90_2d	Exceeding 90th percentiles oftemperature during 5-years exposure window	≥ 2	Low intensity
WMO_90_3d	Exceeding 90th percentiles oftemperature during 5-year exposure window preceding cohort entry	≥ 3	Low intensity
WMO_90_4d	Exceeding 9Oth percentiles oftemperature during 5-year exposure window preceding cohort entry	≥ 4	Low intensity
WMO_92.5_2d	Exceeding 92.5th percentiles oftemperature during 5-year exposure window preceding cohort entry	≥ 2	Middle-low intensity
WMO_92.5_3d	Exceeding 92.5th percentiles oftemperature during 5-year exposure window preceding cohort entry	≥ 3	Middle-low intensity
WMO_92.5_4d	Exceeding 92.5th percentiles oftemperature during 5-year exposure window preceding cohort entry	≥ 4	Middle-low intensity
WMO_95_2d	Exceeding 95th percentiles oftemperature during 5-year exposure window preceding cohort entry	≥ 2	Middle intensity
WMO_95_3d	Exceeding 95th percentiles oftemperature during 5-year exposure window preceding cohort entry	≥ 3	Middle intensity
WMO_95_4d	Exceeding 95th percentiles oftemperature during 5-year exposure window preceding cohort entry	≥ 4	Middle intensity
WMO_97.5_2d	Exceeding 97.5th percentiles oftemperature during 5-year exposure window preceding cohort entry	≥ 2	High intensity
WMO_97.5_3d	Exceeding 97.5th percentiles oftemperature during 5-year exposure window preceding cohort entry	≥ 3	High intensity
WMO_97.5_4d	Exceeding 97.5th percentiles oftemperature during 5-year exposure window preceding cohort entry	≥ 4	High intensity

differences. For complex sampling adjustments in CHARLS data, survey weights were applied using R's 'survey' package to compute robust standard errors. All analyses were conducted using SPSS 27 and R 4.0.5, with statistical significance set at two-tailed $p < 0.05$. Effect estimates were reported as odds ratios (ORs) with 95% confidence intervals derived from the logistic regression models.

Results

Sample characteristics

Typically, 6450 people fulfilled the inclusion criterion and constituted the overall investigation population, with 1129 (17.5%) individuals experiencing a rapid decline in eGFR. The average age was 57.87 ± 8.7 years, with 56.3% of the participants being female ($n = 3634$). We categorized the participants based on the presence of fast loss in renal function (Table 2) and determined that those experiencing a quick decline were more likely to be older ($p < 0.001$). Participants who had quick deterioration in function of the kidney had a higher number of heat wave days in WMO_92.5_2d ($p < 0.001$), WMO_92.5_3d ($p < 0.001$), WMO_92.5_4d ($p < 0.001$), WMO_95_2d ($p = 0.043$), WMO_95_3d ($p = 0.017$), WMO_95_4d ($p = 0.029$), WMO_97.5_2d ($p = 0.002$), WMO_97.5_3d ($p < 0.001$), WMO_97.5_4d ($p = 0.004$).

Exposure to heat wave

Based on the data from the RESDC station, we calculated the number of heat wave days for each city using the 12 heat wave definitions in Table 1 and assigned values to all participants based on their resident addresses. Depending on the specific definition, the average heat wave exposure period per person throughout the investigation ranged from 21.7 to 168.7 days (Table 3). Figure 2A shows the time series of daily average temperatures for the top 20 cities with the highest number of heat wave days. Figure 2B shows the total number of heat wave days and their composition for the top 20 cities.

Association between heat wave exposure and the risk of fast deterioration in renal function

We investigated the relationship between individual exposure to heat waves and the risk of accelerated worsening in the function of the kidney. A heat map was developed to illustrate the trends in the number of heat wave exposure days and the incidence of rapid renal function deterioration five years post-study entry (Fig. 3). The trends indicating an increase in heat wave exposure and the rate of fast kidney function deterioration appeared to be relatively consistent. Figure 4 depicts the relationship between variations in days of the heat wave and the rate of rapid deterioration in renal function. In the completely adjusted Model 3, no significant links were observed between a rapid decline in kidney function and the WMO definitions based on the 90th percentile thresholds for

Table 2 Characteristics of included participants

Variables	**Full cohort**	**Rapid decline in kidney function**		***p*-value**	**95% Confidence Interval**
	***N* = 6450**	**No (*n* = 5321)**	**Yes (*n* = 1129)**		
Age, Mean ± SD	57.869 ± 8.703	57.705 ± 8.662	58.642 ± 8.858	0.001	(57.52, 58.22)
Gender, n (%)				0.079	
Female	3634 (56.341)	3025 (56.85)	609 (53.942)		(55.13%, 57.55%)
male	2816 (43.659)	2296 (43.15)	520 (46.058)		(42.45%, 44.87%)
Stroke, n (%)				0.151	
No	6312 (97.86)	5214 (97.989)	1098 (97.254)		(97.51%, 98.21%)
Yes	138 (2.14)	107 (2.011)	31 (2.746)		(1.79%, 2.49%)
Heart Disease, n (%)				0.584	
No	5712 (88.558)	4718 (88.668)	994 (88.043)		(87.78%, 89.33%)
Yes	738 (11.442)	603 (11.332)	135 (11.957)		(10.67%, 12.22%)
Kidney Disease, n (%)				0.078	
No	6105 (94.651)	5049 (94.888)	1056 (93.534)		(94.10%, 95.20%)
Yes	345 (5.349)	272 (5.112)	73 (6.466)		(4.80%, 5.90%)
Hypertension, n (%)				0.41	
No	4779 (74.093)	3954 (74.309)	825 (73.074)		(73.02%, 75.17%)
Yes	1671 (25.907)	1367 (25.691)	304 (26.926)		(24.83%, 26.98%)
Diabetes, n (%)				0.869	
No	6069 (94.093)	5005 (94.061)	1064 (94.243)		(93.57%, 94.95%)
Yes	381 (5.907)	316 (5.939)	65 (5.757)		(5.05%, 6.43%)
Drinking status, n (%)				0.774	
Non-drinker	4367 (67.705)	3598 (67.619)	769 (68.113)		(66.56%, 68.85%)
Drinker	2083 (32.295)	1723 (32.381)	360 (31.887)		(31.15%, 33.44%)
Smoking status, n (%)				0.185	
Non-smoker	4609 (71.457)	3821 (71.81)	788 (69.796)		(70.38%, 72.56%)
Smoker	1841 (28.543)	1500 (28.19)	341 (30.204)		(27.44%, 29.62%)
HbA1c (%), Mean ± SD	5.266 ± 0.799	5.266 ± 0.8	5.262 ± 0.794	0.875	(5.22, 5.31)
Uric Acid (mg/dl), Mean ± SD	4.361 ± 1.219	4.361 ± 1.214	4.357 ± 1.243	0.915	(4.30, 4.42)
Creatinine (mg/dl), Mean ± SD	0.765 ± 0.179	0.773 ± 0.173	0.727 ± 0.203	< 0.001	(0.744, 0.786)
eGFR, Mean ± SD	93.662 ± 13.976	93.035 ± 13.656	96.616 ± 15.05	< 0.001	(93.321, 94.001)
Changes in the number of heatwave days (day), mean ± SD					
WMO_90_2d	168.726 ± 6.468	168.69 ± 6.476	168.898 ± 6.428	0.324	(167.75, 169.70)
WMO_90_3d	151.46 ± 12.481	151.375 ± 12.429	151.857 ± 12.72	0.247	(150.52, 152.40)
WMO_90_4d	133.407 ± 19.565	133.305 ± 19.459	133.888 ± 20.058	0.372	(131.97, 134.84)
WMO_92.5_2d	124.024 ± 5.882	123.895 ± 5.884	124.633 ± 5.84	< 0.001	(123.78, 124.27)
WMO_92.5_3d	108.38 ± 11.843	108.091 ± 11.801	109.742 ± 11.95	< 0.001	(107.88, 108.88)
WMO_92.5_4d	93.849 ± 17.81	93.47 ± 17.719	95.638 ± 18.134	< 0.001	(92.91, 94.79)
WMO_95_2d	81.537 ± 5.406	81.472 ± 5.353	81.843 ± 5.644	0.043	(81.25, 81.82)
WMO_95_3d	68.981 ± 11.29	68.824 ± 11.249	69.721 ± 11.455	0.017	(68.34, 69.62)
WMO_95_4d	56.072 ± 16.816	55.862 ± 16.835	57.062 ± 16.699	0.029	(55.19, 56.95)
WMO_97.5_2d	37.983 ± 4.521	37.901 ± 4.469	38.37 ± 4.741	0.002	(37.44, 38.52)
WMO_97.5_3d	28.764 ± 8.225	28.57 ± 8.199	29.683 ± 8.29	< 0.001	(28.18, 29.35)
WMO_97.5_4d	21.679 ± 9.128	21.529 ± 9.126	22.389 ± 9.11	0.004	(21.04, 22.31)

two, three, and four consecutive days (Fig. 4A–C). However, significant connections between heat wave days and a rapid decline in kidney function were identified using other WMO definitions.

Subgroup and sensitivity analyses

Figure S1 show the connection between exposure to heat wave days and rapid decline in kidney function, stratified by sex, age, residence, smoking, and alcohol consumption. In summary, our findings suggest a potentially stronger association between exposure to heat wave days and a rapid decline in kidney function among males and younger individuals (Figure S1AB). Compared with participants who did not smoke or drink alcohol, we observed a stronger relationship between exposure to heat wave days and a higher probability of accelerated deterioration in the function of the kidney among those who smoked or drank alcohol (Figure S1CD). The risk

Table 3 Characterization of twelve heat wave definitions from the 2011 to 2015 study

	Min.	q25	Median	Mean	q75	Max
WMO_90_2d	151	164	169	168.7	174	183
WMO_90_3d	113	142	154	151.5	160	178
WMO_90_4d	86	118	136	133.4	147	170
WMO_92.5_2d	110	119	125	124	129	135
WMO_92.5_3d	78	100	107	108.4	117	135
WMO_92.5_4d	52	81	95	93.8	107	126
WMO_95_2d	66	77	82	81.5	85	91
WMO_95_3d	35	61	70	68.9	76	89
WMO_95_4d	23	42	56	56.1	66	89
WMO_97.5_2d	24	35	38	37.9	42	45
WMO_97.5_3d	8	23	30	28.8	36	41
WMO_97.5_4d	4	14	22	21.7	29	38

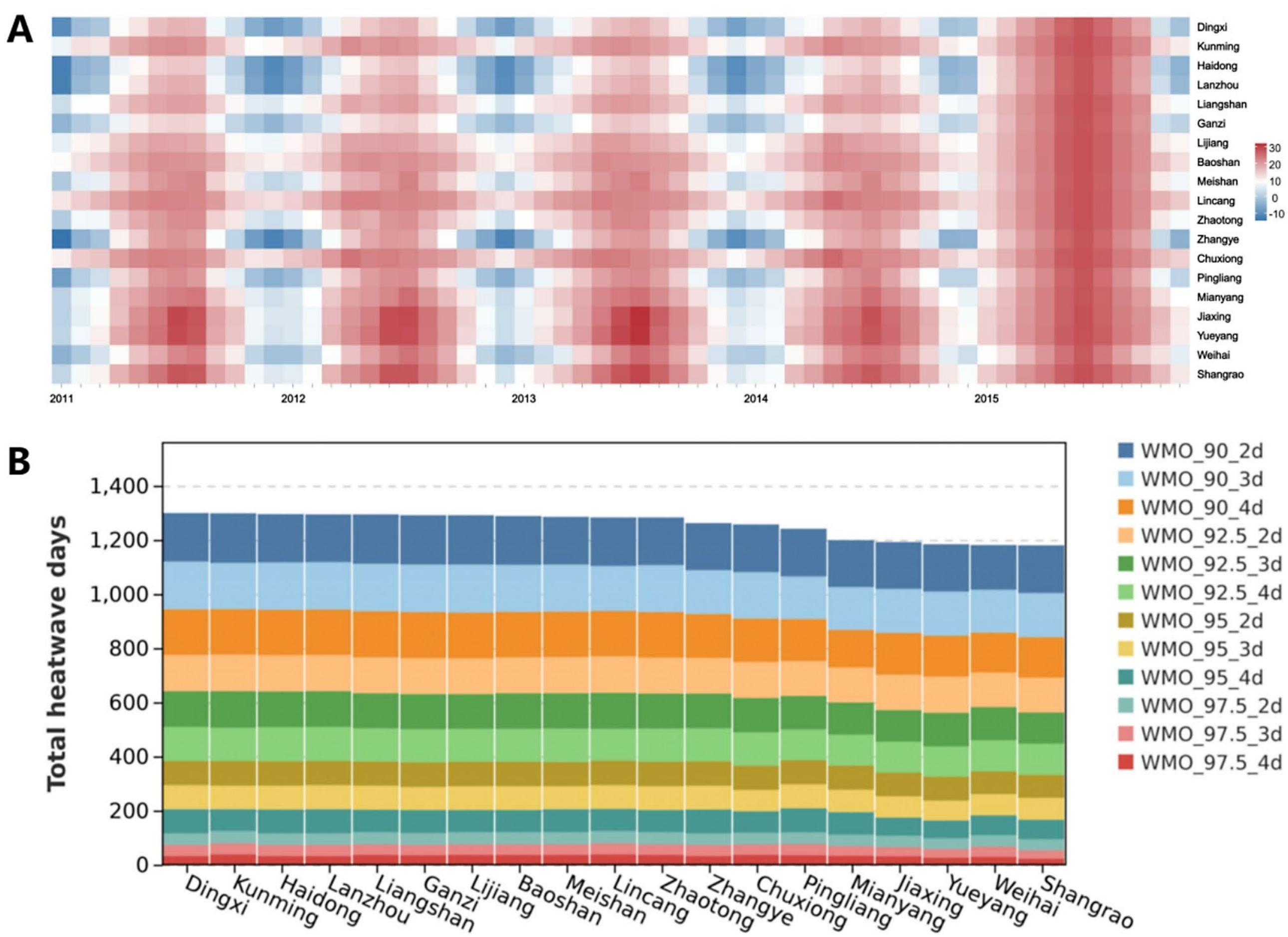

Fig. 2 **(A)** Average daily temperatures in China's top 20 cities with the highest heat wave days, 2011–2015. **(B)** Stacked bar chart of the overall number of heat wave days for the top 20 cities with the highest number of heat wave days in China from 2011 to 2015

estimations for medium-intensity heat wave classifications were significantly greater for urban residents compared to rural ones (Figure S1E).

We conducted sensitivity analyses using two distinct eGFR decline thresholds (30% decline and decline ≥ 5 mL/min/1.73 m^2/year) to assess the robustness of our findings. Results demonstrated consistent associations across all heatwave definitions, with significant risks observed for medium-to-high intensity thresholds (92.5th-97.5th percentiles). The strongest association emerged for the highest-intensity heatwave (WMO_97.5_4d), showing elevated odds ratios for both thresholds (OR = 1.083 for 30% decline; OR = 1.0755 for ≥ 5 mL/min/1.73 m^2/year

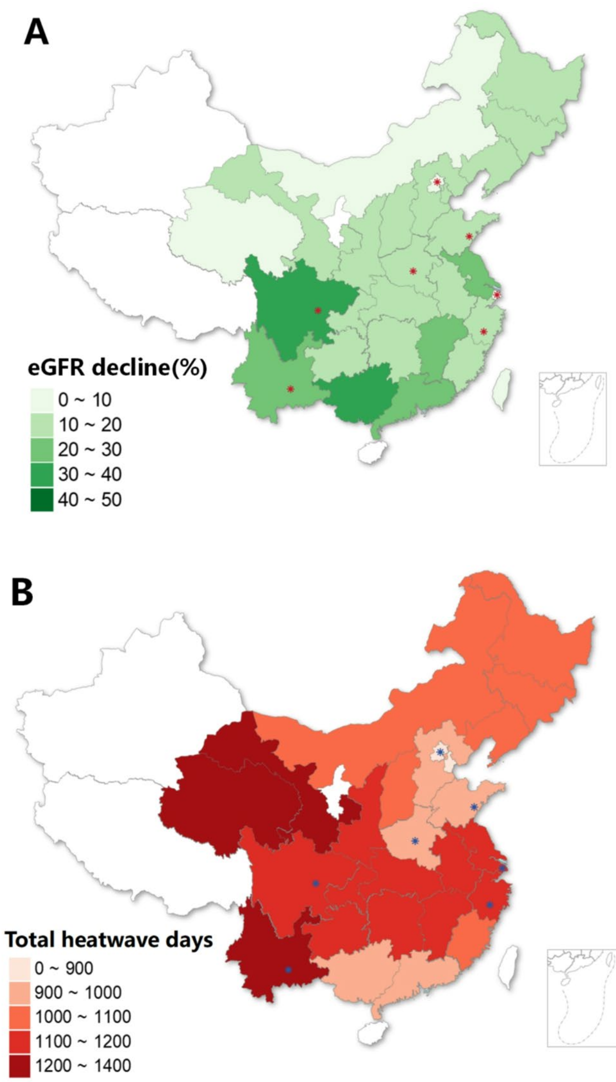

Fig. 3 Geographic distributions of heat wave and estimated glomerular filtration rate (eGFR) decline rate. The six-pointed star indicates the location of the center. **(A)** The proportion of incidents of rapid decline in kidney function in 4 years after entry of the study represented as a percentage (%). **(B)** Annual total heat wave days from 2011 to 2015 derived from the Resource and Environment Science Data Center of the Chinese Academy of Sciences (RESDC)

decline), further supporting a dose-response pattern (Table S1).

Discussion

It is anticipated that projected rises in temperature in a warm climate will have a significant impact on kidney health [24], with older adults potentially experiencing the most pronounced effects.

This investigation utilized a systematic approach to evaluate the relations between heat wave exposure and renal function decline among older adults, utilizing a national database that encompasses a diverse range of geographical regions in China.

First, we discovered that the rise in middle to high-intensity heat wave events was connected with a significant risk of rapid kidney function decline, suggesting increased heat wave intensity was associated with deterioration of renal function. Moreover, we confirmed that the connections between heat wave and rapid kidney function decline were robust after further adjustment of age, gender, medical history, drinking status, smoking status, and biochemical. The findings of this study indicate that heat wave exposure is an independent risk factor for the rapid decline in renal function observed in patients during such events.

The outcomes of our investigation indicated that there were disparate relationships among populations of varying ages and genders. Specifically, younger adults and males exhibited a marginally elevated correlation between heat wave exposure and a precipitous decline in renal function compared to other demographic groups. Similar outcomes have been detected in the earlier investigations [25]. One potential explanation is that younger adults may engage in outdoor activities for a greater proportion of their time than older individuals under similar circumstances [26], which may consequently elevate their exposure to elevated temperatures. As with our findings, previous studies have also identified a higher risk of hospitalization due to kidney disease in males than in females [13, 27]. Another two studies discovered greater risks of smokers' or drinkers' death in extremely high temperatures [28]. Similar to these studies, we found analogous results regarding the correlation between heat wave and kidney function decline in these two categories.

Our findings demonstrate that middle-to-high intensity heatwave exposure (defined by 92.5th-97.5th percentile thresholds over ≥ 2 days) is associated with 23–38% increased odds of rapid kidney function decline (OR 1.23–1.38 in fully adjusted models). These results align with and extend current evidence through three key dimensions: First, the biological plausibility of our effect sizes is supported by acute biomarker studies. A 2024 JAMA trial found that 3-hour dry-heat exposure (47 °C) induced acute creatinine elevations of 0.17 mg/dL in elderly adults [29], equivalent to 40% of our rapid decline threshold (3 mL/min/1.73 m^2/year). While direct temporal comparisons are limited, this suggests repeated subclinical injury from heatwaves may cumulatively manifest as longitudinal eGFR decline. Second, our high-intensity heatwave effects mirror chronic progression patterns observed in CKD populations. The 2024 Lancet DAPA-CKD trial analysis revealed that each 30-day exposure to heat index > 30 °C accelerated eGFR decline by 0.6% annually (β=-0.6%, 95%CI:-0.9 to -0.3) [30]. For a baseline eGFR = 60 mL/min/1.73 m^2, this translates to ~0.36 mL/min/1.73 m^2/year decline—comparable to our threshold when compounded over 8–10 heatwave seasons. Third,

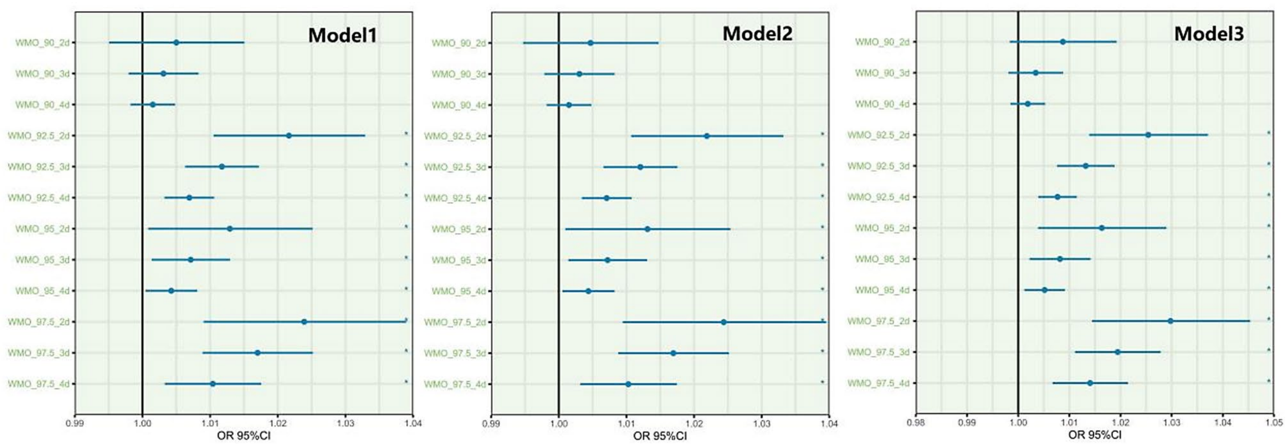

Fig. 4 Adjusted odds ratios (OR; 95% confidence interval (CI)) for the rapid decline in kidney function due to heat wave exposure. Model 1 is unadjusted; Model 2 adjusts for age and sex; Model 3 further accounts for baseline eGFR, hemoglobin, serum uric acid, chronic kidney disease, hypertension, diabetes, stroke, cardiovascular disease, smoking, and alcohol use

our stratified analyses revealing heightened vulnerability in males (OR 1.42 vs. 1.18 in females) and urban residents align with Zhang et al.'s nationwide study showing 22% greater CKD risk from extreme temperatures in urban vs. rural areas [31]. In comparison to previous studies, our investigation contributes to the current body of knowledge by addressing some of the gaps in understanding the impact of heat waves on the kidney function decline of elderly people.

The decline in renal function observed during heat waves likely results from interconnected physiological pathways exacerbated by aging-related vulnerabilities. Prolonged heat exposure induces systemic dehydration through thermoregulatory sweating, leading to hemoconcentration that may transiently elevate serum creatinine while concurrently reducing renal plasma flow through neurohormonal activation of the sympathetic nervous system and renin-angiotensin axis [32–35]. These hemodynamic alterations increase intraglomerular pressure, creating mechanical stress that accelerates glomerulosclerosis, particularly in elderly individuals with pre-existing vascular stiffening [36, 37]. Concurrently, heat-induced mitochondrial dysfunction generates reactive oxygen species that promote tubular inflammation and fibrosis through TGF-β1 and NLRP3 inflammasome activation [38, 39], while subclinical rhabdomyolysis from exertional heat stress may cause cumulative tubular injury [40]. Nocturnal heat exposure further compounds risk through sleep disruption and blunted nighttime blood pressure dipping patterns [41], a critical recovery period for renal homeostasis. Urban environments may amplify these effects through heat island intensification and pollution-mediated oxidative stress [42], with lifestyle factors like smoking and alcohol use potentiating endothelial dysfunction [43]. Our findings of stronger associations with higher-intensity exposures and vulnerable subgroups align with this multifactorial pathophysiology, where repeated thermal insults overwhelm compensatory mechanisms in aging kidneys with diminished functional reserve.

The escalating threat of heat-related CKD progression necessitates a multi-pronged mitigation framework spanning environmental regulation, clinical innovation, and community engagement. Early warning systems tailored for nephrology patients should integrate real-time biometric monitoring through wearable devices, building upon Beijing's risk-stratified heat alert mechanism that demonstrated 23% reduction in heat-related hospitalizations among vulnerable populations [44]. Urban planning must prioritize green infrastructure in high-risk neighborhoods, where epidemiological modeling reveals each 10% increase in green space coverage correlates with 2.3% decrease in heat-attributable mortality – a finding validated across 93 European cities through satellite thermal imaging and mortality data linkage [45]. Clinically, heat exposure screening should be incorporated into routine nephrology assessments, complemented by WHO-endorsed hydration protocols adapted from Central American sugarcane worker interventions that reduced occupational heat stress incidents by 58% through mandated cooling breaks and electrolyte supplementation [46]. Workplace policies need reformation informed by the DAPA-CKD trial evidence showing accelerated eGFR decline (0.6% per 30 high-heat days) among outdoor laborers [47], while digital health platforms could leverage AI prediction models from Chinese cohort studies achieving 90% accuracy in CKD progression forecasting [48]. These interventions synergize with China's Healthy Cities initiative, with exposure-response models projecting 21–34% reduction in heat-driven CKD progression through integrated implementation [44].

Our study has several limitations requiring careful interpretation. First, the use of city-level temperature data as a proxy for individual exposure might inadequately capture microclimate variability and behavioral modifiers (e.g., outdoor duration, air conditioning use), potentially causing exposure misclassification that could bias estimates toward the null. Second, the exclusion of participants lacking serum creatinine measurements may introduce selection bias. Third, while encompassing diverse Chinese regions, generalizability to other climatic zones requires verification. Finally, the study lacked data on herbal medicine/nephrotoxic drug use (unavailable in CHARLS), potentially influencing kidney outcomes. While adjusted for key factors, this gap underscores the need for future research incorporating detailed medication/environmental toxin data to clarify heatwave-kidney links.

It is particularly noteworthy that the CHARLS database itself presents inherent constraints: Exclusion of institutionalized/severely ill individuals underrepresents heat-vulnerable groups, biasing estimates. Uneven attrition (older rural residents), urban-rural response gaps (72% vs. 65%), and healthier profiles (lower smoking) limit generalizability. Partially offset by longitudinal design, future studies should integrate heat sensors, geolocation, and localized climate data to enhance accuracy.

Notwithstanding the limitations mentioned above, the dataset employed in this analysis offers a distinctive chance to address a pivotal question about climate's impact on the kidney. The data indicate a correlation between elevated temperatures and a decline in the function of kidneys among the elderly population. The outcomes lend support to the view that ambient environmental heat exposure plays a clinically meaningful role in the exacerbation of disease progression in older patients. In light of the anticipated rise in global temperatures, it is imperative to assess the efficacy of strategies aimed at decreasing the risk of heat wave-related illness in the elderly as part of a holistic approach to disease management.

Conclusion

In conclusion, this study contributes to the existing body of evidence by clarifying the link between heat wave exposure and kidney function decline in older adults. The implementation of adaptive strategies to safeguard kidney function during periods of elevated temperatures may prove beneficial in ensuring consistent renal function in older adults. Such strategies could be particularly advantageous for vulnerable groups, including males, urban dwellers, smokers, drinkers, and individuals of relatively younger age. Additional study is necessary to validate these results and clarify the underlying processes.

Abbreviations

CHARLS	China Health and Retirement Longitudinal Study
CKD	Chronic Kidney Disease
CKD-EPI	Chronic Kidney Disease Epidemiology Collaboration
eGFR	Estimated Glomerular Filtration Rate
RESDC	Resource and Environment Science Data Center
WMO	World Meteorological Organization-based (heatwave definitions)
ADL	Activities of Daily Living
CIs	Confidence Intervals
ORs	Odds Ratios
GPS	Global Positioning System
HbA1c	Glycated Hemoglobin
SD	Standard Deviation
ANOVA	Analysis of Variance

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12889-025-22822-0.

Supplementary Material 1

Supplementary Material 2

Acknowledgements
The authors wish to thank the participants of the CHARLS.

Author contributions
YL and BZ contributed to the study design. JZ and BW performed the data analysis and completed the original manuscript. BY participated in the revision of this manuscript. All authors have approved the final manuscript.

Funding
This research was supported by the Zhejiang Provincial Medical and Health Science and Technology Program (2024KY665), the Zhejiang Provincial Traditional Chinese Medicine Science and Technology Project (2024ZL287), the Zhejiang Provincial Medical and Health Science and Technology Program (2023KY545), the Zhejiang Provincial Medical and Health Science and Technology Program (2022KY524), and the Fundamental scientific research project of Hangzhou Medical College (KYQN2023009).

Data availability
The database (CHARLS), which is used in this paper, is publicly available. (https://charls.pku.edu.cn/).

Declarations

Ethical approval and consent to participate
All participants provided informed consent, and the research methodology received approval from the Ethical Review Committee of Peking University (approval number: IRB00001052-11015).

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Received: 15 December 2024 / Accepted: 16 April 2025
Published online: 30 April 2025

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