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Examining the non-linear association between ambient temperature and mental health of elderly adults in the community: evidence from Guangzhou, China

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Abstract

The association between ambient temperature and mental health has been explored previously. However, research on the psychological effect of temperature in vulnerable groups and neighborhood scales have been scarce. Based on the survey and temperature data collected from 20 neighborhoods in Guangzhou, China, this study estimated the association between ambient temperature and community mental health among the elderly, adopting a fixed-effects methodology. According to this empirical analysis, compared to a comfortable temperature range of 20℃–25℃, measures of worse mental health among elderly were significant in high and low temperatures with increases in negative outcomes observable at both ends of the temperature range, leading to the U-shaped relationship. Second, the association between ambient temperature and worse mental health was found in the subcategories of gender, income, and symptom events. Specifically, from the hot temperature aspect, elderly males were more sensitive than elderly females. The effect on the low was far more than on the middle-high income group, and the probability of each symptom of the elderly's mental health significantly increased. From the cool temperature aspect, the temperature in the range of 5ºC–10ºC was significantly associated with the probability of some symptoms (feeling down, not calm, downheartedness, and unhappiness) and the middle-high income group. Our research enriches the empirical research on ambient temperature and mental health from a multidisciplinary perspective and suggests the need for healthy aging and age-friendly planning in Chinese settings.

Keywords Mental health, Livability, The elderly, Ambient temperature, Community, Guangzhou

Introduction

The global surface temperature has increased by 1.1ºC in 2011–2020 compared to that in 1850–1900. This temperature has increased faster since 1970 than in any other 50-year period for at least the last 2000 years [1]. The warming rate in China is higher than the global level during the same period. The average surface temperature in 2022 is 0.92ºC higher than usual, making it one of the three warmest years since the beginning of the twentieth century [2]. Human health, one of the most important factors affected by climate change, is now recognized as a global research priority [3]. The relationship between

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environmental conditions and mental health has long been recognized and has recently attracted more attention in the field of climate change, especially in vulnerable groups [4]. Temperature change stress can trigger not only physiological responses in human bodies (such as heat rash, muscle cramps, dizziness) [5], negative birth outcomes [6], and heat-related mortality [7], but also to mental health outcomes (such as negative expressed sentiment, mental disorders, self-harm) [8, 9]. According the Global Burden of Disease (GBD), the proportion of global disability-adjusted life-years (DALYs) attributable to mental disorders is 4.9% [10]. The epidemiological association between climate change and mental health [11], which is critical for understanding and effectively planning for the ways in which variations in weather and climate conditions will impact population mental health in the future [12], is being increasingly examined.

A robust body of literature outlines the impact of climate change on mental health outcomes. In existing heat-health literature, some studies have found the risks of a range of mental health-related outcomes with high temperatures [12, 13]. For instance, mental illness-related hospital admissions (such as mental disorder) and emergency department visits for conditions increased with high temperatures [14, 15]. Adverse meteorological conditions, including cold temperatures, hot temperatures, precipitation, and narrower daily temperature ranges, were all associated with worsened expressions of sentiment [16]. The association between temperature and suicide rates indicated a significant increase in monthly suicides per 1°C increase in mean monthly temperature of 0.68% in the USA and of 2.1% in Mexico [11]. Another study showed that the linkage of ambient outdoor temperature and community mental health was that higher temperatures were associated with worse outcomes [17].

As for the association between temperatures and mental health, psychological well-being is affected by ambient temperatures and this relationship is linear and mediated [18]. Mullins and White presented causal evidence of a robust negative relationship between increasing temperatures and mental well-being [12]. In recent years, some evidence has demonstrated the presence of a U-shaped relationship where extreme cold and extreme heat led to increased mental health [15]. For example, Li et al. found that compared to the human comfortable temperature range of 60°F –70°F, additional cold and hot days in the past month reduced the probability of self-reported mental health difficulties [3].

Theoretically, temperature could affect mental health via three mechanisms [19]. The first set of mechanisms is physiological harm; for instance, high and low temperatures lead to alterations in blood flow or serotonin levels, which are detrimental to people's mental well-being. The second set of mechanisms is cognitive change. Such changes in cognitive state may be attributed to temperature-driven behavior alterations. Evidence suggests that temperature impacts conflict and aggressive behavior [20, 21], sleep (disrupted sleep at high temperatures) [22], and functional brain connectivity [23]. The third set of mechanisms is societal changes. Research has shown that temperature impacts stress resulting from reduced economic and agricultural outputs. For instance, Carleton demonstrated links between high temperatures and increased suicide rates through impacts on crop yields in India [24]. Temperature also impacts increased alcohol consumption [25].

In the subgroup analysis of individual or contextual population characteristics, greater vulnerability has been documented in terms of age (elderly), sex, socioeconomic factors (national income), and temperature zones. For instance, Åström et al. found that the elderly population was more vulnerable to heat waves in morbidity and mortality [26]. Liu et al. determined that the male group showed statistically significant positive associations in mental health-related mortality and morbidity, while slightly lower risk was observed in females [4]. Gao et al. reported that middle and high national income levels showed a significant association between ambient temperature and suicide, and the subgroup of middle national income level showed lower heterogeneity [27]. Temperate and tropical zones were found to have a significant association between ambient temperature and suicide incidence [28, 29].

While considerable scholarly attention has focused on the effect of temperature on mental health in developed countries, surprisingly, less empirical research has focused on the psychological effect of temperature in Chinese cities, especially in vulnerable groups and neighborhood micro-scale. Some studies have revealed the association between temperature and community mental well-being in Chinese cities using survey questionnaires. For instance, Xue et al. found that a 1 °C increase in mean temperature was associated with a 3% higher risk of an increasing depressive symptoms score between 2010 and 2014. Yang et al. tested the U-shape relationship between temperature and health status, whereas the elderly were more sensitive to extreme heat. Nevertheless, these studies were based on a macro-scale and less attention to specific groups, especially the elderly group in the aging context.

Guangzhou is port city of rapid urbanization and population aging, located in the Pearl River Delta, with a marine subtropical monsoon climate characterized by hot and humid summers, mild winters. According to 2019 Guangzhou Climate Bulletin, the annual average temperature in Guangzhou is 23.1 °C in 2019, which was

0.9 ℃ higher than usual, while winter temperatures can be below 10 °C. The average temperature from April to October was above 23 ℃, while the rest of the months were below 21 ℃. The annual rainfall is 2336 mm, making the climate in Guangzhou relatively adverse for the megacity's aging population. This study explores the linkage between ambient temperature and community mental health among the elderly using survey data collected from 20 neighborhoods in Guangzhou, China. The impact of extreme weather on different categories of socioeconomic characteristics and mental health symptoms was also investigated. This research extends previous literature in several respects. First, most studies have focused on the extreme heat effects on human health under global warming rather than cold events. The relationship between cold temperatures and human health is explored in this study. Second, this study focuses on the elderly's mental health in the context of climate change. Third, it focuses in the particular on the extent to which temperature interval and symptoms affect the community mental health of the elderly.

Study design

Study area and cross-sectional survey

Guangzhou, one of the first-tier cities in China, is located in the southeast of China. With the increase in urbanization (urbanization rate was 86.48% in 2022) and population aging (the proportion of aged 60 and above population aging is 18.86% in 2022) in Guangzhou, a substantial proportion of the megacity's aging population is exposed to climate change threats and their adverse effects.

A face-to-face survey was implemented in Guangzhou from December 2018 to April 2019. According to the definition of the elderly of WHO (World Health Organization) and Chinese context, the following inclusion criteria of the interviewer were applied: (1) aged 60–90; (2) a resident or had resided in Guangzhou for over 6 months; and (3) able to understand and help the investigator complete the questionnaire. According to factorial ecological analysis and proportion of permanent residents in 6th population census, twenty residential neighborhoods were selected from the districts of Liwan, Yuexiu, Haizhu, Tianhe, Baiyun, Huangpu, Panyu, and Huadu, including house type of historical neighborhoods, danwei neighborhoods, urban villages, commercial housing, affordable housing areas, and rural villages (Fig. 1). With the help of the neighborhood committee staff and communication of investigators, participants who met the above requirements were finally determined. All participants involved in this study gave their informed consent, and this study had been approved by institutional review board of school of geography and planning, Sun Yat-sen University. Any study exclusion criteria were applied to the study.

A multi-stage stratified probability proportionate to population size sampling technique was used to select elderly participants in each neighborhood. In the first stage investigation, proportion of permanent residents in 6th population census was selected with probabilities proportional to size to determine specific neighborhood unit, referring to the population sampling survey rules of the China's National Bureau of Statistics. In the second stage investigation, sample households from each neighborhood were randomly selected using a systematic sampling approach. The Kish grid method was used to choose a respondent in each sampled household, specifically, taking into account the variables of age and gender comprehensively for the stratification. A trained interviewer administered each questionnaire in a face-to-face interview with an elderly participant. According to criteria of elderly population above reaching 10% using Chinese sixth national population census, the experimental sample size was estimated for sample size estimation, the alpha error probability was set to 0.05, and the statistical efficacy was set to 0.95, which showed that a total sample size of at least 231 individuals was needed for this study. Finally, 1000 study participants were enrolled. Actually, 966 individual-level valid observations were obtained (Table 1).

Data measures

Outcome

Mental health (MH) is defined as a state of emotional well-being, which was measured by mental health parameters in the 36-item Short-Form Health Survey (SF-36) [30]. It consists of five items related to feelings of nervousness, feeling down, calmness and peace, downheartedness and blues, and happiness experienced over the past four weeks. Each item is rated on a six-point Likert scale, ranging from "all of the time" to "none of the time." The Cronbach's alpha of the mental health items had good internal consistency (0.924). The initial mental health score is calculated for each individual on a metric scale ranging from 5 (worst mental health outcome) to 30 (best mental health outcome). According to the scoring instructions of SF-36, mental health item is scored on a 0 to 100 range based on the Eq. (1). The formula for the SF-36 mental health score is as follows:

$$MH\ score = \frac{(Initial\ score - lowest\ score)}{25} \times 100 \quad (1)$$

In this study, the 100-MH score was regarded as a dependent variable to ensure that the impact of high and low temperatures on elderly's mental health is

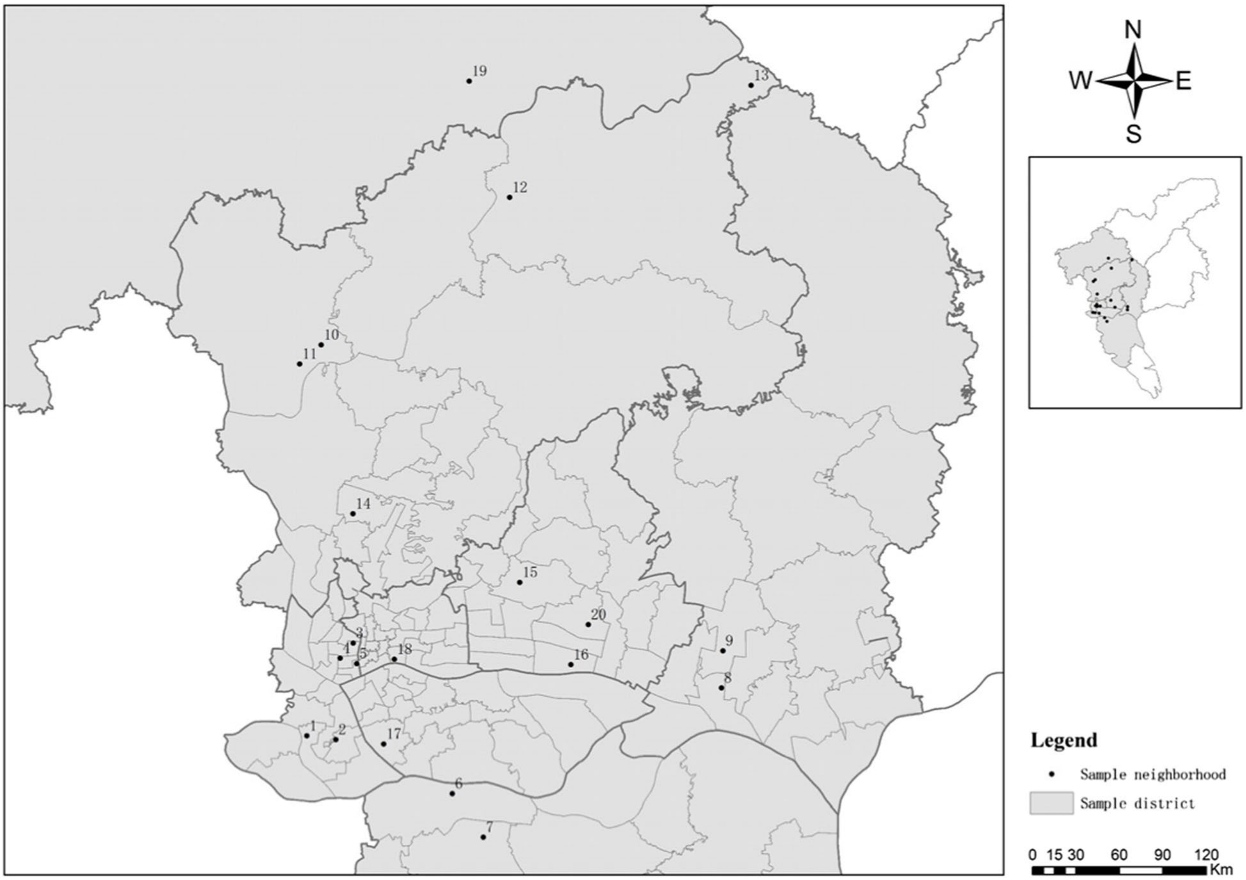

Fig. 1 Study area

understandable. The scoring of top 50% was relatively in better mental health status, while the scoring of last 50% was relatively in worse mental health status.

Weather variables

Street- and town-level apparent temperature data (maximum, minimum, mean apparent temperature) were derived from the Guangzhou Meteorological Bureau. These data were restricted to January to April 2019. The questionnaire was distributed from December 2018 to April 2019 (winter and spring seasons), the temperatures in January to March 2019 were selected for analysis, which was consistent with the time of questionnaire conduction, and given that respondents to questionnaires reported mental health status over the "past four weeks". The selection of the street/town meteorological station should be in line with the case neighborhoods. In total, the daily mean temperatures for 19 meteorological stations were obtained for the study period. The mean temperature in this study was focused, noting that it will be correlated with maximum and minimum temperatures. The temperature data were aggregated to a monthly level by taking the average weight of daily and hourly temperatures. For temperature, dummy variables were constructed to represent the average temperature range. The mean apparent temperatures were divided into six groups, which were 5°C–10°C, 10°C–15°C, 15°C–20°C, 20°C –25°C, 25°C–30°C, and > =30°C, dummy variables ranged from 1 to 6. In addition, within the temperature range of 18°C–23℃, the human body does not feel thermal stress; therefore, 20°C–25°C was set up as a control group in this study [31]. The purpose of setting temperature intervals is to explore the non-linear effect of temperature on the mental health of the elderly.

Covariates

Socioeconomic and demographic covariates, including age (chronological age), gender, educational attainment, marital status, hukou status,[1] monthly household income, employment information, etc., were controlled in this

[1] Under China's household registration system, also known as the hukou system (In Chinese), people have urban or rural hukou.

Table 1 Summary statistics for the sampled neighborhoods

Neighborhood name	District	Jiedao	House type	Number of questionnaires completed	Numbers of aged 65 and above	Sampling rate
Dashan village	Panyu	Dashi	Urban village	56	384	14.58%
Dengtang village	Baiyun	Zhongluotan	Rural village	52	936	5.56%
Fanghehuayuan	Liwan	Dongjiao	Affordable housing	22	454	4.85%
Guang'ao	Panyu	Luopu	Commercial housing	23	350	6.57%
Guangchuanheyuan	Liwan	Baihedong	Danwei	110	1149	9.57%
Hengsha	Huangpu	Dasha	Urban village	32	492	6.50%
Huafu	Liwan	Longjin	Historical	10	358	2.79%
Huagong	Tianhe	Wushan	Danwei	94	2636	3.57%
Huangpuhuayuan	Huangpu	Huangpu	Commercial housing	32	288	11.11%
Jiang village	Baiyun	Jianggao	Rural village	20	637	3.14%
Jinshazhou	Baiyun	Jinsha	Affordable housing	92	968	9.50%
Meilinhaian	Tianhe	Yuancun	Commercial housing	36	249	14.46%
Shanxia village	Huadu	Huadong	Rural village	49	353	13.88%
Tangdehuayuan	Tianhe	Tangxia	Affordable housing	8	232	3.45%
Tangyong village	Tianhe	Xinshi	Urban village	38	228	16.67%
Xingxian	Liwan	Hualin	Historical	29	417	6.95%
Yangrendong	Liwan	Lingnan	Historical	28	421	6.65%
Zhibei	Haizhu	Nanshitou	Danwei	128	1236	10.36%
Zhu'er village	Baiyun	Zhongluotan	Rural village	35	534	6.55%
Zhujiang	Yuexiu	Zhuguang	Historical	72	531	13.56%

study, as suggested in previous literature. Participants answered the above questions about socioeconomic and demographic information. We treated the covariates of gender, educational attainment, marital status, hukou status, employment information as discrete variables, while variables of age, monthly household income were treated as continuous variables. The summary statistics for all variables are shown in Table 2.

As for other control of the weather variable, some researchers have found that, among other humidity measures, specific humidity contributes the most to human well-being [32]. Hence, due to the correlation between temperature and humidity, humidity data were regarded as the control variable, which was also processed by the same method as the temperature data. Humidity data (maximum, minimum, mean) were derived from the Guangzhou Meteorological Bureau. Also, these data were restricted to January to April 2019.

Methods

Baseline analysis

Due to nonlinearities reflected by temperature range relationships, omitted variable bias, and etc., we further include a set of fixed effects to identify the linkage between ambient temperature and the elderly's health: individual fixed effect accounted for time-invariant characteristics of socio-economic and demographic information, place (neighborhood) fixed effect controlled for time-invariant differences in unobserved mental health across geographies unit. More specifically, we adopt a fixed-effects methodology that has become standard in previous literature to identify the causal impacts of ambient temperature on the elderly's mental health [33]:

$$Y_{ic} = \beta_0 + \sum_{k=1}^{6} \beta_k * Temp_{ck} + X_{ic} + W_c + \mu_i + \delta_c \quad (2)$$

In Eq. (2), we describe the model for estimating the effects of temperature on mental health outcome, where Y_{ic} is the individual i outcome of the elderly's mental health in neighborhood c. $\sum_{k=1}^{6} \beta_k * Temp_{ck}$ captures the effect of temperature bin k, which ranges from less than 10 °C to more than 30 °C-by-5°C-wide bins with a 20°C–25°C bin omitted as the base. $Temp_{ck}$ is the number of days in the month that fall into the 5°C-wide mean temperature bin k in Guangzhou. This specification for measuring the effects of temperature on mental health is semi-parametric and allows for arbitrary nonlinearities in the relationship [12]. X_{ic} represents the participants' socio-economic and demographic information, such as age, gender, educational attainment, and marital status. W_c is another control of the weather variable, in this

Table 2 Summary statistics of demographical information ($N = 966$)

Variable	Description	Mean/Proportion (Standard Deviation)	Variable	Description	Mean/Proportion (Standard Deviation)
Covariates	Age	69.335 (7.770)	Covariates	Employment information	
	Gender			Full-time	3.62%
	Male	43.17%		Part-time	2.17%
	Female	56.83%		Retired	70.81%
	Educational Attainment			Unemployed	3.21%
	Primary school or below	41.41%		Farming	20.19%
	Junior high school	27.85%		Weather control	
	Senior high school or technical secondary school	28.05%		Relative humidity	76
	College or above	2.69%	Outcome	Mental Health	59.019 (15.349)
	Marital status		Predictors	Temperature in bins	
	Married	77.02%		5℃-10℃	8.1
	Single	1.24%		10℃-15℃	13.2
	Divorced or widowed	21.74%		15℃-20℃	17.9
	Hukou status			20℃-25℃	22.4
	Local	68.94%		25℃-30℃	26.4
	Non-local	31.06%		> = 30℃	32.3
	Monthly household income	2243.913 (2454.823)			

study, humidity was selected as weather control variable. μ_i and δ_c represent individual- and place- (neighborhood) fixed effects, respectively. All correlation coefficients should reach statistically significant level ($p < 0.1$). This study used STATA 14 to carry out all the data analysis.

Stratified analyses

To explore potential variations in the association between ambient temperature and mental health of elderly adults across strata of gender and income, we stratified the aforementioned baseline analyses for gender (male vs. female) and income (middle and high income vs. low income). The following empirical models describe the exact specifications used for gender and income different group.

$$GenderY_{ic} = \beta_0 + \sum_{k=1}^{6} \beta_k * Temp_{ck} + X_{ic} + W_c + \mu_i + \delta_c \tag{3}$$

$$IncomeY_{ic} = \beta_0 + \sum_{k=1}^{6} \beta_k * Temp_{ck} + X_{ic} + W_c + \mu_i + \delta_c \tag{4}$$

In Eq. (3) and Eq. (4), the empirical models for each outcomes were very similar, but distinctions were required for each due to either the sample or the nature of the outcome variable. $GenderY_{ic}$ is the male/female individual i outcome of the elderly's mental health in neighborhood c. $IncomeY_{ic}$ is the middle and high/low income individual i outcome of the elderly's mental health in neighborhood $c.X_{ic}$ represents the participants' socio-economic and demographic information except gender or income variable. Other variables were aforementioned in 2.3.1 section. This study used STATA 14 to carry out all the data analysis.

Results

Descriptive characteristics

Among the 1000 participants selected for the study, 966 (96.60%) participants completed the survey. Due to incomplete response of mental health items in the questionnaire, 34 participant samples were excluded. The 966 participants had a mean age of 69 years, half of them were female, their education background was concentrated mainly in the "secondary school and below" category (97.31%), 77.02% of the participants were married, most of them were retired (70.81%), half of them were residents (68.94%). The 966 participants' average monthly income was 2243.913 RMB, lower than the per capita disposable income of permanent urban residents (according to Guangzhou Statistical Yearbook in 2020). The respondents reported relatively low mental health scores (59.019). The indicators of weather variables showed mean temperature in bins and mean relative humidity. The descriptive characteristics are presented in Table 2.

Table 3 Effect of ambient temperature on the probability of the elderly's mental health outcomes

	Model 1a	Model 1b	Model 1c
Temperature	Mental health	Mental health	Mental health
> =30℃	2.015**	2.096**	2.417**
25℃-30℃	-0.239	-0.268*	-0.216
15℃-20℃	-0.864	-0.838	-0.815
10℃-15℃	0.466	0.387	0.302
5℃-10℃	0.526*	0.478*	0.410*
Control			
Individual	Y	Y	Y
Place	-	Y	Y
Weather	-	-	Y
Adjusted R^2	0.639	0.712	0.734
AIC	3068.032	2999.052	2968.032
BIC	3096.298	2964.044	2894.012

Note: * $p < 0.10$, ** $p < 0.05$. A temperature bin of 20ºC–25ºC is omitted as the reference

Associations between ambient temperature and the elderly's mental health

Table 3 shows the marginal effects of temperature on reports of the elderly's mental health. Each model represents different regressions with additional controls to show how confounders impact the relationship between temperature and mental health. The baseline regression results are shown in Table 3. The results in Model 1a indicated that compared to the comfortable temperature range of 20ºC–25ºC, the score of elderly's bad mental health significantly increased by 2.015 and 0.526 points when the average temperature was higher than 30ºC and in the range of 5ºC–10ºC. Model 1b added individual characteristic variables, namely gender, age, income, Hukou, etc. Model 1c further controlled for other weather variables, including relative humidity, which showed full regression results (including individual covariates and weather variables) for this specification. Specifically, for individual characteristics, gender (β = 0.096, $p < 0.01$), and monthly household income (β = 0.401, $p < 0.1$) were positively related to the elderly's mental health outcome, while relative humidity was not significantly associated with the elderly's mental health outcome. Model 1c contained strict control, and is the preferred specification to explain the remaining results. In general, the probability of reporting the mental health outcomes of the elderly was linked with relatively cooler and hotter ambient temperatures, and the negative impact of average temperature above 30℃ on elderly individual mental health outcomes is much greater than the impact of low temperature.

Comparison between temperature and each symptom of mental health

This study investigated the impact of ambient temperature on the severity of each mental health symptom by estimating the impact of temperature on the score of each item. Table 4 shows the results of the regression of ambient temperature on the elderly's mental health in each symptom. The results indicated that high temperatures significantly increased the probability of each symptom of the elderly's mental health. Compared to 20ºC–25ºC, average temperature higher than 30ºC significantly increased scores of nervousness (β = 0.478, $p < 0.05$), feeling down (β = 0.428, $p < 0.05$), not calm (β = 0.415, $p < 0.05$), downheartedness (β = 0.132, $p < 0.05$), and unhappiness (β = 0.465, $p < 0.$ 1). Similarly, the average temperature between 5ºC–10ºC increased the probability of some symptom of the elderly's mental health. Specifically, the temperature in the range of 5ºC–10ºC significantly increased the probability of feeling down (β = 0.165, $p < 0.1$), not calmness (β = 0.192, $p < 0.1$), downheartedness (β = 0.141, $p < 0.1$), and unhappiness (β = 0.177, $p < 0.1$). The temperature in the range of 25ºC–30ºC significantly decreased the probability of downheartedness (β = -0.158, $p < 0.1$). Overall, the estimated coefficients for these two temperature ranges were much smaller than those for average temperatures above 30ºC.

Stratified analysis of socioeconomic characteristics

The analysis of the association between ambient temperature and the elderly's mental health was stratified and statistically significant associations were observed. Ambient temperature was associated with the elderly's mental health outcomes in the gender and income groups. The stratified analysis results are presented in Table 5.

In gender sub-groups, the significant differences in physiological conditions between male and female groups could account for the differences between their ability to adapt and regulate ambient temperatures. The heterogeneous effects of ambient temperature on the mental health outcomes of the elderly in different genders were estimated in Models 3a and 3b (Table 5). High temperatures (temperature above 30ºC) were significantly associated with the mental health outcomes in the male and female groups. However, elderly males were more sensitive to the effects of high temperatures. Compared to temperature in the range of 20ºC–25ºC when the temperature was higher than 30ºC, the mental health outcomes for elderly males increased by 2.109 points, and the female group increased by 1.958 points. The result revealed that the elderly males were more susceptible to high temperatures, which may be attributed to age and physique differences. This result further suggested that

Table 4 Effect of ambient temperature on the elderly's mental health in each symptom

	Model 2a Nervous	Model 2b Feeling down	Model 2c Not calm	Model 2d Downhearted	Model 2e Unhappy
Temperature					
> =30℃	0.478**	0.428**	0.415**	0.132**	0.465*
25℃-30℃	-0.134	-0.089	-0.121	-0.158*	-0.152
15℃-20℃	-0.121	-0.147	0.105	0.269	0.172
10℃-15℃	0.156	0.188	0.276	0.289	0.369
5℃-10℃	0.138	0.165*	0.192*	0.141*	0.177*
Control variables					
Gender (Ref: male)	0.482**	0.310**	0.500**	0.476**	0.522**
Age	-0.259	-0.412	-0.398	-0.350	-0.301
Income	0.414*	0.579	0.522*	0.510	0.409
Hukou (ref: local)	0.329	0.321	0.372	0.306	0.391
Educational Attainment (ref: Primary school or below)					
Junior high school	0.589	0.377	0.591	0.467	0.505
Senior high school or technical secondary school	0.312	0.327	0.183	0.492	0.303
College or above	0.193	0.491	0.362	0.377	0.500
Employment information (ref: retired)					
Full-time	0.682	0.571	0.502	0.644	0.582
Part-time	-0.116	0.268	0.636	0.357	-0.384
Unemployed	-0.425	-0.834	-0.641	-0.546	-0.421
Farming	0.653	0.543	0.536	0.370	0.574
Marital status (ref: married)					
Single	-0.396	-0.645	0.206	0.733	-0.642
Divorced or widowed	-0.398	-0.668	-0.553	0.561	0.767
Relatively humidity	0.688	0.741	0.781	0.690	0.809
Adjusted R^2	0.681	0.647	0.703	0.715	0.743
AIC	3021.022	3122.144	3362.259	3294.623	3313.211
BIC	3039.156	3136.024	3399.982	3301.269	3365.563

Notes: * $p < 0.10$, ** $p < 0.05$. Temperature bin of 20–25℃ is omitted as the reference

climate change may exacerbate gender inequality in mental health among the elderly.

In the income sub-group, the environment of the low- and middle-high income groups differed, and the significant differences in the two groups were affected by ambient temperatures. Considering the number of samples and the per capita monthly income in Guangzhou, we selected the elderly with personal monthly income less than 3000 yuan as the low-income group, and the rest were the middle-high-income group. The research results are shown in Models 4a and 4b (Table 5). Models 4a and 4b indicate that, compared to the temperature in the range of 20°C–25°C, an average temperature above 30°C significantly increased the mental health scores of the elderly in both the low and middle-high income groups. Specifically, the elderly low-income group was more sensitive to the effects of high temperatures. When the temperature was higher than 30°C, the mental health outcome score for the low-income group increased by 2.860 points, and the middle-high income group increased by 2.455 points. The possible reason is that the low-income group had worse environments, including living conditions, recreational places, etc., which also indicated that the temperature adaptation ability of the elderly low-income group was insufficient. Model 4b also indicates that in the temperature range of 5°C–10°C, the low-income group was more susceptible to low temperatures. One potential mechanism of the beneficial mental effect of cooler temperatures could be the better sleep quality in subtropical regions.

Discussion

Main findings

Compared to the previous literature, we found a non-linear relationship between temperatures and mental health in the elderly. Overall, compared to a comfortable temperature range of 20°C–25°C, worse mental health measures of the elderly responded significantly to both high

Table 5 Effect of ambient temperature on the elderly's mental health in gender and income group

	Model 3a Male	Model 3b Female	Model 4a Middle and high income	Model 4b Low-income
Temperature				
> =30℃	2.109***	1.958**	2.455**	2.860**
25℃-30℃	-0.277	-0.198	-0.388	-0.353
15℃-20℃	0.178	0.167	-0.183	-0.254
10℃-15℃	0.282	0.575	0.296	0.210
5℃-10℃	1.912	0.512	-0.266	0.273*
Control variables				
Gender (Ref: male)			0.392*	0.377*
Age	-0.408	-0.299	-0.501*	-0.411
Income	0.561*	0.390*		
Hukou (ref: local)	0.502	0.719	0.119	0.327
Educational Attainment (ref: Primary school or below)				
Junior high school	0.378	0.421	0.481	0.600
Senior high school or technical secondary school	0.414	0.404	0.286	0.357
College or above	0.371	0.621	0.389	0.481
Employment information (Ref: retired)				
Full-time	0.592	0.610	0.459	0.553
Part-time	-0.536	-0.511	-0.462	-0.401
Unemployed	0.381	0.567	0.533	0.609
Farming	0.298	0.383	0.395	0.401
Marital status (ref: married)				
Single	0.204	0.430	0.701	0.642
Divorced or widowed	0.805	0.596	0.704	0.612
Relatively humidity	0.718	0.510	0.591	0.402
Adjusted R^2	0.596	0.652	0.698	0.706
AIC	3630.264	3201.316	3233.796	3154.841
BIC	3796.353	3235.452	3365.397	3210.465

Notes: * $p<0.10$, ** $p<0.05$, *** $p<0.01$. Temperature bin of 20–25℃ is omitted as the reference

(above 30°C) and low temperatures (5°C –10°C), with increases in negative outcomes observable at both ends of the temperature range leading to the U-shaped relationship. Thompson et al. showed that an inverted U-shaped relationship might exist between heat and general mental health or well-being [19]. White also found a day under 40°F or over 80°F led to an increase in emergency department (ED) visits on the day of the event [34]. High temperature was correlated with increased mental distress, which was consistent with previous literature in most cases. Based on data from 2 243 395 unique individuals of ED visits, Nori-Sarma et al. found that days of extreme heat were associated with an IRR of 1.08 (95% CI, 1.07–1.09) for ED visits for any mental health condition [35]. Qiu et al. have found that the relative risk of acute hospital admission increased for depression, schizophrenia, and bipolar disorder in the US Medicare population for each 5°C increase in short-term exposure to cold season temperature, [36]. Increasing mean apparent temperature was found to have acute associations with mental health outcomes and intentional injuries by Basu et al. (2017) [9]. Consistent with previous studies, hot temperature was usually associated with worse outcomes of mental health. However, the effect of cool temperature is a little more controversial. For example, cooler temperature was not significantly associated with better outcomes of self-reported mental health [13]; some researchers have observed that cooler temperatures could decrease emergency department visits and suicides related to mental health [12]. Cooler days in the past month have also been found to reduce the probability of reporting days of bad mental health [3].

Subgroup analyses

Associations between ambient temperature and worse mental health were found in this study, as well as for the subcategories of gender, income, and symptom events. The heterogeneity was significantly associated in male and female groups with hot temperature as temperature exposure indicator, while the hot temperature effect on males was far more than that of females. Some studies have shown that males were more vulnerable than females on account of the difference in outdoor activity, exposing the male group to ambient temperature more frequently. Consistent with previous studies, Gao et al. showed that completed suicide was more relevant to temperature increase compared with attempted suicide [27]. Stivanello et al. found that male mental health department patients had significantly higher temperature-related mortality odds than the corresponding groups in the non-mental health department population, probably because they suffer the effects of numerous vulnerable factors. Several factors might explain why the elderly males affected had worse mental health outcomes could be because they are particularly vulnerable to adverse ambient conditions, such as high temperatures [37]. In the in-depth interview, some elderly participants replied that their chronic disease and chronic health conditions, such as cardiovascular, respiratory diseases, and diabetes [38], impaired thermoregulatory responses to heat stress [39]. In addition, the elderly suffering from worse mental health outcomes might have limited coping mechanisms when faced with high temperatures, such as finding colder environments, wearing appropriate clothing, drinking more water [38], and gaining access to healthcare [40].

In this study, the subgroup analysis of income showed that hot temperature was related to both middle-high and low groups. In contrast, the hot temperature effect of the low-income group was much more than that in the middle-high income group. A previous study of mental health impacts associated with high ambient temperatures by Gao et al. (2019) showed that in both middle and high income locations, temperature increase was significantly associated with suicide, and the IRR of middle-income-level areas was higher than that in high-income-level areas [27]. The country-level relative risk of high temperature on suicide was higher in the male group than in the female group [41]. Additionally, a relationship between latitude and temperature thresholds for mental health-related mortality was identified [4], with lower minimum mortality temperatures observed in higher latitudes [42]. However, cool temperature was related to the middle-high income group, suggesting possible physiological adaptation in this group. The possible reason is that the low-income group who live in poor areas have no extra money to buy air conditioners and other cooling equipment to reduce heat stress [27], especially in subtropical regions in China. The middle-high income group was not vulnerable to cooler temperatures, one cause was likely that due to good living conditions and long-term exposure to high temperatures, and the occasional low temperature could change their mood.

In the subgroup analysis of symptom categories of mental health, high temperature was significantly related to the probability of each symptom. Previous studies also showed the influence of temperatures on emotional state and behavior [43]. In terms of mental health symptoms, central body and brain temperature could be increased on account of heat exposure, leading to slow brain processing capacity or sensation of environmental factors. The elderly coping ability and lower threshold might have greater difficulties in managing hot environmental situations, which in turn can exacerbate worse outcomes of mental health [44]. Cool temperature was significantly related to the probability of some symptoms. For example, Baylis et al. (2018) reported the expression of negative emotions on Facebook and Twitter increased in cooler days [16]. The association between symptom categories of mental health and ambient temperature revealed that the U-shaped relationship existed in the elderly.

Potential mechanisms between ambient temperature and the elderly's mental health

The impacts of ambient temperature exposure on the mental health of the elderly are evident from our findings. However, the underlying mechanisms are complex. According to pathophysiological mechanisms, high temperatures are likely to affect the levels and balance of neurotransmitters serotonin and dopamine in the brain, which play a role in emotions, cognitive function, and complex task performance [45, 46]. In addition, individual physiological and behavioral adaptation strategies may be challenged when faced with hot temperatures, irritability, and psychological distress, etc., being more common [9]. Evidence from previous studies has shown that cognitive function, mood state, and mental performance were adversely impacted by high temperature exposure [47], explaining why dementia increased in hospitalizations during heatwaves [48].

Another potential mechanism of the mental effect of ambient temperature could be sleep disruption. Previous studies analyzed the effects of factors other than temperature on sleep, revealing the relationship between sleep deprivation and poor mental health (irritability, frustration, and negative emotions, etc.) [49, 50]. In addition, sleep disturbances and sleep deprivation were associated with high or low night temperatures, especially among the elderly [51], explaining the bio-plausibility of the temperature-mental health relationship.

Heat stress may also play a role in mental health. These ambient temperature changes in the brain may reduce the elderly cognitive awareness of the environment and their ability to engage in adaptive behaviors (for example, wearing appropriate clothing), which in turn makes them more susceptible to the effects of temperature stress [4]. Therefore, the elderly with worse mental health, such as mental illness, may be susceptible to the effects of temperature change [52]. However, heat stress cannot explain why cold temperatures affect the incidence of negative mental health outcomes, as posed by Mullins and White (2019) [12].

Limitation

This study has several limitations. First, the cross-sectional study had a limited capability of drawing a causal inference regarding the evaluated associations between ambient temperature and the mental health of the elderly. Second, self-reported questionnaires were applied to obtain subjective data on the mental health of the elderly. The way the mental health question was framed might influence elderly respondents to narrow or broaden the meaning of the question. Third, regional contextual and community-level factors, such as neighborhood environment, social cohesion, precipitation, greenspace, air pollution, etc., may play a mediating role in the impact on the mental health outcomes of the elderly. Fourth, this study did not report on whether the study participants had self-reported pre-existing mental health issues. Therefore, this may have confounded the results as those with mental health issues may be more likely to self-report adverse mental health outcomes.

Conclusion

The study estimated the association between ambient temperature and community mental health among the elderly using survey data collected from 20 neighborhoods in Guangzhou, China. Results indicated that compared to the comfortable temperature range of 20ºC–25ºC, worse mental health measures of the elderly responded significantly to high and low temperatures, with increases in negative outcomes observable at both ends of the temperature range, leading to the U-shaped relationship. Second, the association between ambient temperature and worse mental health outcomes was found in the subcategories of gender, income, and symptom events. Taken together, the results of this study point to the importance of ambient temperature in addressing the need for mental health and crisis services within the elderly population in middle-income countries. Hence, further research is needed to address the remaining questions and limitations of this study and understand how a broad array of environmental factors affect the mental health of the elderly.

The need to support researchers and practitioners analyzing the mental health effects of ambient temperature is acknowledged. Understanding how to address temperature changes in mental health requires understanding the mechanisms through which the impacts operate. To ensure the optimization of moderate temperature environments for the elderly, we should improve the environmental quality (such as increasing green and blue space, highly reflective road surfaces, etc.) to create moderate temperatures. Additionally, district cooling could be adopted based on surface temperature, terrain, land use, building density, etc., to form thermal environment guidance zoning, which could facilitate the better realization of "age-friendly" planning.

Abbreviations

GBD	Global Burden of Disease
DALYs	Disability-adjusted life-years
WHO	World Health Organization
MH	Mental health
SF-36	Short-Form Health Survey

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Authors' contributions

Conceptualization, Y.C. and Y.Y.; methodology, Y.C.; software, Y.C.; validation, Y.C.; formal analysis, Y.C.; investigation, Y.C.; resources, Y.Y.; data curation, Y.C.; writing-original draft preparation, Y.C.; writing-review and editing, Y.C., Y.Y; supervision, Y.Y.; project administration, Y.Y.; funding acquisition, Y.C. and Y.Y.

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Availability of data and materials

The datasets presented in this article are not readily available because of institutional copyright issues. Requests to access the datasets should be directed to Yuan Yuan, yuanyuan@mail.sysu.edu.cn.

Declarations

Ethics approval and consent to participate

The studies involving human participants were reviewed and approved by School of Geography and Planning, Sun Yat-sen University Ethics committee. The participants provided their oral informed consent to participate in this study.

Consent for publication

Not applicable.

Competing Interests

The authors declare no competing interests.

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