Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Climate Change: Who Is Bearing the Burden?—Extreme Weather Risks, Intergenerational Support, and the Health of Middle-Aged and Older Adults

You bu WANG
Xinjiang University
We jie ZHANG
1164781799@qq.com

Xinjiang University of Finance and Economics

Research Article

Keywords: extreme climate risks, health of middle-aged and older adults, intergenerational support, climate innovation patents, extreme heat

Posted Date: November 4th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11387468/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Climate Change: Who Is Bearing the Burden?— Extreme Weather Risks, Intergenerational Support, and the Health of Middle-Aged and Older Adults

Abstract

Actively addressing the risks posed by population aging and climate change is a major national strategic priority; however, the comprehensive impact of extreme weather risks on the health of middle-aged and older adults, as well as the mechanisms through which these impacts occur, still require further investigation. Based on data from the five waves of the China Health and Retirement Longitudinal Study (CHARLS) from 2011 to 2020, this study matches meteorological data at the prefecture-level city level to construct an unbalanced panel comprising 43,228 observations. It employs a two-way fixed-effects model to examine the impact of extreme weather risks on the health of middle-aged and older adults and utilizes the instrumental variables method to mitigate potential endogeneity issues. The study found the following: First, extreme weather risks significantly reduce the health status of middle-aged and older adults. This conclusion holds even after a series of robustness tests, including changing instrumental variables, propensity score matching, double machine learning, controlling for COVID-19 interference, altering the sample scope, substituting the dependent variable, bilateral truncation, adding control variables, and adjusting fixed effects; Second, a mechanism analysis indicates that extreme climate risks lead to deteriorating health among middle-aged and older adults through intergenerational support channels, such as increasing the burden of care for grandchildren, reducing upward economic support, and weakening intergenerational emotional interactions; Third, heterogeneity analysis reveals that middle-aged and older adults—particularly women, those with higher incomes and educational attainment, and those residing in the central and eastern regions—experience more significant negative impacts from extreme climate risks; Fourth, further analysis shows that extreme heat is a major contributor to health deterioration among middle-aged and older adults. Mitigating patents and adaptive patents play distinct roles in the process by which extreme heat affects their health: mitigating patents can partially offset health losses, whereas the suppression of adaptive patents exacerbates negative effects.

Keywords: extreme climate risks; health of middle-aged and older adults; intergenerational support; climate innovation patents; extreme heat

1. Introduction and Literature Review

As the country with the world’s largest elderly population, China is experiencing an accelerating aging process; as of 2024, the population aged 60 and older exceeded 310 million, accounting for 22% of the total population (Jin et al., 2024).According to United Nations projections, by 2050, China’s population aged 60 and older will account for nearly one-third of the total population (United Nations Department of Economic and Social Affairs, 2024).Extreme climate risks are environmental factors that cannot be ignored in the current context, as they affect residents’ physical and mental health. The health vulnerability of middle-aged and elderly individuals in the

face of climate shocks has become a major environmental health issue and a challenge for social governance, directly impacting people’s livelihoods and high-quality population development. Compared to other demographic groups, middle-aged and older adults experience a decline in physiological functions and have weaker resilience to risks, making them more susceptible to health damage caused by extreme weather. Within this vast elderly population, the increasing health vulnerability of middle-aged and older adults—particularly the health risks posed by extreme heat—has become a critical issue that all sectors of society urgently need to address. Against this backdrop, the state has successively issued top-level policy documents that balance the dual objectives of addressing population aging and preventing and controlling health risks associated with climate change. The “15th Five-Year Plan” Outline proposes to “thoroughly implement the national strategy to actively address population aging, improve policy mechanisms for the coordinated development of elderly care services and industries, and promote a future where the elderly are provided for, remain active, and enjoy life (State Council of the People’s Republic of China, 2026).”The “National Strategy for Adaptation to Climate Change 2035” states that “research on the health impacts of climate change and major extreme weather and climate events—such as heat waves and floods—should be conducted to identify the primary health risks posed by such events, as well as the characteristics of vulnerable regions and populations (Ministry of Ecology and Environment of China, 2022).” Therefore, investigating the impact of extreme climate risks on the health of middle-aged and older adults and their underlying mechanisms is not only a practical necessity for actively addressing climate change and mitigating environmental health risks, but also an essential step toward promoting healthy aging and improving the public service support system for the elderly.

In recent years, there has been a growing body of literature on how climate change affects the health of older adults. Tropical cyclones are not only the most destructive extreme weather events, but also the only disasters that depend simultaneously on oceanic thermal conditions and atmospheric dynamic processes; the energy sources, destructive mechanisms, and secondary disasters associated with tropical cyclones all exhibit strong nonlinear relationships with key climate change parameters (Wang et al., 2025).Extreme weather events—such as heavy rainfall, drought, and abnormal temperatures—can have widespread and far-reaching effects on human physical and mental health (Ban et al., 2019;.Dimitrova et al., 2021).Extreme heat waves are significantly associated with the incidence and mortality rates of circulatory and respiratory diseases (Tian et al., 2013).Extreme heat can significantly increase the incidence and mortality rates of respiratory diseases and cardiovascular and cerebrovascular diseases (Xi et al., 2024;Zhang et al., 2024;Cheng et al., 2018);temperatures above 30 ℃ significantly increase the likelihood of depression (Hua et al., 2023).Extreme heat can trigger physical illnesses, induce negative psychological emotions such as anxiety and depression, increase the economic burden, and exacerbate social instability; it can also alter lifestyle habits—such as sleep patterns—which in turn can lead to a deterioration in mental health (Dell et al., 2009;Hsiang et al., 2013;Ranson ., 2014;Carleton ., 2017;Obradovich et al.,

2017;Obradovich et al., 2018;White ., 2017;Karlsson and Ziebarth .,2018).In addition, exposure to cold snaps and heat waves increases the risk of comorbidities among middle-aged and older adults (Tang et al., 2025).Exposure to extreme heat events is significantly associated with a decline in mental health scores among older adults; this negative impact is mediated through pathways such as increased prevalence of chronic diseases, reduced physical activity, and decreased contact with children (Guo et al., 2025).A study in China has further revealed that the health vulnerabilities of middle-aged and older adults in the country when faced with heat waves exhibit distinct spatiotemporal variations (Fang and Wang .,2025).In addition to heat waves, the health effects of abnormal precipitation also warrant attention. Studies have shown that an increase in the number of days with extreme precipitation has a significant negative impact on the mental health of middle-aged and older adults, resulting in socioeconomic costs that should not be underestimated (Zhang et al., 2025).

Nevertheless, most existing studies rely on single extreme-weather indicators and lack comprehensive composite risk measurements. The literature largely focuses on direct health consequences of extreme weather and insufficiently examines the mediating role of intergenerational support. Micro-level empirical evidence on differentiated mediating effects of climate-innovation patents under extreme heat remains limited. Accordingly, drawing on five-wave CHARLS data (2011-2020), this paper addresses four research questions: (1) Do extreme-climate risks generate adverse health outcomes for China’s middle-aged and older adults? (2) What intergenerational-support mechanisms mediate these health impacts? (3) Do these effects exhibit multi-dimensional heterogeneity across subgroups and geographic regions? (4) What differentiated mediating roles do mitigation-oriented and adaptation -oriented climate-innovation patents play in the extreme-heat-to-older-adult-health relationship?

This study makes four main marginal contributions. First, adopting the perspective of composite extreme-climate risks and middle-aged-and-older-adult health enriches research on elderly-population health and supplements existing literature. Second, this paper identifies three intergenerational-support mediating pathways: increased grandchild-care burden, reduced upward economic support and weakened intergenerational emotional interactions, providing theoretical support and empirical evidence for precise optimisation of public-health services and elderly-health security policies. Third, unpacking multi-layered heterogeneity delivers policy evidence for stratified, refined governance to advance the Healthy China strategy. Fourth, by focusing specifically on extreme-heat health effects and differentiating mitigation versus adaptation climate-patent mechanisms, this study expands empirical work at the climate-health research intersection.

2 Theoretical Analysis and Research Hypotheses

2.1 The Impact of Extreme Weather Risks on the Health of Middle-Aged and Older Adults

The theory of vulnerability originated in the study of natural disasters and was later extended to the field of older adult health. Health vulnerability among older adults is defined as a state in which their health is below normal levels and

unsustainable, given the older adult population's low risk tolerance (Deng and Feng ., 2021).As they age, middle-aged and older adults experience a gradual decline in physiological function, and their bodies' ability to adapt and mitigate risks continues to weaken, making them more vulnerable to complex external environmental shocks such as extreme weather. Multiple climate events—including extreme heat, extreme precipitation, and drought—can not only trigger acute episodes of chronic physical illnesses, leading to physical health deterioration, but also disrupt the order of daily life, amplify life's uncertainties, and give rise to negative psychological emotions such as anxiety and depression. In China, family-based care remains the primary model of elderly care. Most middle-aged and older adults live in ordinary households that lack specialized disaster-protection infrastructure and supporting services, making it difficult to effectively shield them from the multiple health disruptions caused by extreme weather. Consequently, their overall physical and mental well-being suffers.

Hypothesis 1. Extreme-weather risks exert significant adverse effects on the health status of middle-aged and older adults.

2.2 Mediating Mechanisms Through Which Extreme Weather Risks Affect the Health of Middle-Aged and Older Adults

Role-strain theory (Goode, 1960) posits that individuals may face broad, dispersed and sometimes conflicting role obligations. Each role relationship demands diverse activities or responses that must be fulfilled within given time-space constraints. When individuals are forced to bear multiple role responsibilities exceeding their capacity, limited personal time and energy become persistently strained, readily producing physical-mental stress and impaired health. Intergenerational grandchild care represents a very common household-labour arrangement in contemporary China. Extreme-weather risks can disrupt adult children's work and daily life; harsh weather constrains mobility and raises family-life pressures, reducing adult children's capacity for direct grandchild care and shifting caregiving duties onto middle-aged and older grandparents (Hughes et al., 2007). Prior studies show that intergenerational care negatively impacts older adults' physical and mental health (Hughes et al., 2007). Grandparents acting as primary grandchild caregivers have double the depression risk compared with non-caregiving grandparents (25.1 % versus 14.5 %) (Minkler et al., 1997). Intensive caregivers frequently show clinical depressive symptoms and limitations in activities of daily living (Minkler and Fuller-Thomson, 2001). Domestic Chinese research also confirms adverse health consequences of grandparental caregiving (Xiao, 2017). Sustained caregiving stress erodes older adults' rest-and-recovery time and intensifies physical -mental strain.

Hypothesis 2. Extreme-weather risks harm the health of middle-aged and older adults by increasing the burden of caring for grandchildren.

Social-exchange theory interprets human social behaviour as cost-benefit-based exchange processes (Blau, 1964; Homans, 1961). Altruistic motives and exchange motives together constitute a dual framework for understanding intergenerational economic support: altruism emphasises affection-driven transfers without expectation

of direct reciprocity; exchange perspectives stress reciprocal equivalent economic give-and-take. Altruistic and reciprocal logics dominate intergenerational economic transfers between rural Chinese parents and children (Ning & Wang, 2015). Financial transfers from adult children constitute critical material security for many middle-aged and older adults, sustaining quality of life and access to medical-wellness resources. However, extreme-weather events can undermine this support in two ways. Extreme heat significantly lowers financial transfers from adult children to elderly parents (Wang and Wang, 2025). Meanwhile, extreme weather raises household living costs and disaster-prevention-mitigation expenditures and may generate business-income losses for adult children, forcing them to tighten household budgets and cut financial support for older parents. Diminished upward economic support restricts disposable resources for middle-aged and older adults, squeezes health-enhancing spending, weakens risk-buffering capacity and ultimately damages health outcomes.

Hypothesis 3. Extreme-climate risks exert adverse health impacts on middle-aged and older adults by reducing upward economic support from adult children.

The stress-buffering hypothesis provides a classic theoretical framework explaining how social support mitigates stress-related health harms (Cohen and Wills, 1985). Social support protects individuals from pathogenic stressor effects by providing interpersonal resources responsive to needs triggered by stressful events, acting as an emotional buffer to mitigate negative psychological consequences and lower risks for stress-related disorders such as anxiety and depression (Cohen and Wills, 1985). Within intergenerational-support systems, intrafamilial emotional companionship and communication represent key emotional-social-support resources that alleviate psychological stress for older adults. Nevertheless, extreme-weather events disrupt travel conditions and hinder in-person family gatherings and face-to-face communication, weakening this stress-buffering function. Simultaneously, life uncertainties generated by severe weather can induce negative emotions among family members and reduce willingness to initiate communication, lowering intergenerational emotional-interaction frequency and eroding emotional bonds. Middle-aged and older adults rely heavily on family-provided emotional comfort. Insufficient emotional support amplifies loneliness and anxiety; accumulated long-term psychological stress further impairs physical health. Existing evidence shows that more annual hot days reduce children’s emotional support for older parents, with emotional support mediating 19.3 % of heat-exposure-driven declines in self-rated health (Wang and Wang, 2025).

Hypothesis 4. Extreme-climate risks adversely affect the health of middle-aged and older adults by weakening intergenerational emotional interactions.

3 Research Design

3.1 Data Sources

The data in this paper are primarily drawn from the China Health and Retirement Longitudinal Study (CHARLS). This database was implemented under the leadership of the National School of Development at Peking University, drawing on the established practices of international studies such as the Health and Retirement Study (HRS) in the United States and the English Longitudinal Study of Aging (ELSA), and

employs a multistage, stratified, probability-proportional-to-size (PPS) sampling method. It covers 150 counties (districts) and 450 villages (neighborhoods) across 28 provinces (autonomous regions and municipalities) nationwide. The study aims to systematically collect household and personal information on middle-aged and older adults aged 45 and above, thereby providing high-quality public microdata for research on aging. This paper uses national follow-up data from five waves of CHARLS: 2011, 2013, 2015, 2018, and 2020. Data on city-level variables are primarily sourced from the "China Urban Statistical Yearbook" for the corresponding years. The study processed the raw data as follows: (1) Retained observations for individuals aged 45 and older; (2) Observations with severe missing values or logical errors in key variables were excluded; (3) Based on the city and year information associated with each observation, the CHARLS individual-level data were matched with city-level variables from the "China Urban Statistical Yearbook" to generate the analytical dataset required for the study. Ultimately, an unbalanced panel dataset comprising 43,228 observations across the five waves was obtained.

3.2 Model Specifications

Since this paper uses panel data, a two-way fixed-effects regression model is employed.

$$\text{Health}_{ict} = \alpha + \beta \cdot ECR_{ct} + \gamma \mathbf{X}_{ict} + \mu_i + \lambda_t + \varepsilon_{ict} \quad (1)$$

Here, is the dependent variable, representing the composite health index of individual i in city c in year t; is the core independent variable, representing the extreme climate risk index of city c in year t; is a vector of control variables, including individual-level, household-level, societal-level, and city-level variables; is the individual fixed effect, used to control for individual heterogeneity that does not change over time; is the time fixed effect, used to absorb macroeconomic shocks at the national level; is the random error term.

Where Health_{ict} = composite health index for individual i, city c, year t; ECR_{ct} = extreme-climate-risk index of city c in year t; $\mathbf{X}_{ict}$ = vector of multi-level control variables (individual, household, social-security and city-level covariates); μ_i = individual fixed effects absorbing time-invariant individual heterogeneity; λ_t = year fixed effects absorbing national-level macro-shocks; ε_{ict} = stochastic error term.

3.3 Variable Definitions

Dependent Variable: Health of Middle-Aged and Older Adults. This variable consists of three dimensions: physical health, mental health, and social health. First, at the level of physical health—that is, the integrity of an individual's bodily functions and their ability to perform activities of daily living—the study measures physical health from both subjective and objective perspectives. Subjective physical health is assessed using a self-rated health indicator, measured by the question in the CHARLS questionnaire: "How would you rate your health? "Do you consider your health to be very good, good, fair, poor, or very poor?" in the CHARLS questionnaire. Responses are assigned continuous values ranging from 1 to 5 (1 = very poor, 5 = very good), with higher values indicating better subjective perceptions of physical health. Objective physical health is measured by the sum of two indicators: Activities

of Daily Living (ADL) and Instrumental Activities of Daily Living (IADL). The CHARLS ADL scale includes six items: dressing, bathing, eating, getting in and out of bed, using the toilet, and controlling bowel and bladder functions. In this study, a score of 1 was assigned to each item where the respondent reported difficulty, and a score of 0 was assigned to items where no difficulty was reported. The total score ranges from 0 to 6, with a higher score indicating poorer ability in activities of daily living. The IADL scale consists of six items: housework, cooking, shopping, making phone calls, taking medication, and managing finances. The same scoring method is applied, resulting in a score range of 0 to 6; a higher score indicates poorer instrumental activities of daily living ability. Second, at the psychological level—that is, an individual's emotional state and mental well-being—the study used the Center for Epidemiological Studies Depression Scale (CES-D 10) to measure the level of depression among middle-aged and older adults. The CES-D 10 scale in the CHARLS questionnaire consists of 10 items: "I worry about trivial matters," "I have difficulty concentrating on tasks," "I feel down," "I find it hard to do anything," "I am hopeful about the future," "I feel afraid," "I have trouble sleeping," "I feel happy," "I feel lonely," and "I feel I cannot go on with my life." Each item is rated on a 4-point scale: "Rarely or never" (0 points), "Not very often" (1 point), "Sometimes or half the time" (2 points), and "Most of the time" (3 points); the two positive emotion items, "I am hopeful about the future" and "I feel happy," are reverse-scored. The total score for the 10 items ranges from 0 to 30; a higher score indicates a higher level of depression and poorer mental health. Finally, regarding social health—that is, the adaptive interaction between middle-aged and older adults and their social environment, as well as their subjective perceptions—the study measures this across two dimensions: life satisfaction and social participation. Life satisfaction is measured using the item coded as dc026 in the CHARLS questionnaire, which asks: "Overall, are you satisfied with your life?" Responses are scored on a 5-point scale: "Very satisfied" is assigned a value of 5, "Somewhat satisfied" a value of 4, "Somewhat dissatisfied" a value of 3, "Somewhat dissatisfied" a value of 2, and "Very dissatisfied" a value of 1; a higher value indicates greater life satisfaction. Social participation is measured using eight specific behaviors related to social and intellectual activities from the CHARLS questionnaire. The four social activities include: interacting with friends; going dancing, exercising, or practicing qigong; participating in community-related organizations; and volunteering or helping others. The four intellectual activities include: playing mahjong, cards, or chess; attending educational or training courses; investing in stocks; and using the Internet. This study measures participation at two levels: breadth and depth. Breadth is calculated by directly summing the "yes" or "no" responses for the eight activities, with a score range of 0–8 points; participation depth is calculated by summing the frequency scores for the eight activities (never = 0 points, rarely = 1 point, irregularly = 2 points, almost weekly = 3 points, almost daily = 4 points), with a range of 0–32 points; a higher score indicates a deeper level of social participation. Based on the above three dimensions and seven indicators, the entropy method was used to synthesize the seven indicators into a composite measure of health for middle-aged

and older adults. The specific breakdown is shown in Table 1.

Table 1 Health Indicator System for Middle-Aged and Older Adults

Level 1 Indicators	Level 2 Indicators		Indicator Attributes
Physical Health	Subjective	Self-rated Health	Positive (+)
	Objective	Activities of Daily Living (ADL)	Negative (−)
		Instrumental Activities of Daily Living (IADL)	Negative (−)
Mental Health	Depression Index (CES-D)		Negative (−)
	Life Satisfaction		Positive (+)
Social Health	Social Adaptation	Breadth of Participation	Positive (+)
		Depth of Participation	Positive (+)

Explanatory variables. The core explanatory variable is Extreme Climate Risk (ECR). Following (Guo et al., 2024;Ma and Wang ., 2026), we adopt the Climate Physical Risk Index (CPRI). This index is constructed based on daily observational data from global weather stations and integrates four types of events: extreme low temperatures (LTD), extreme high temperatures (HTD), extreme precipitation (ERD), and extreme drought (EDD).Using the period from 1973 to 1992 as the baseline, the 10th and 90th percentiles of daily average temperature, the 95th percentile of daily precipitation, and the 5th percentile of daily humidity at each station were determined as thresholds. the cumulative number of days per year for which each station exceeded the thresholds for the four types of events was calculated, mapped to the city level, and averaged to obtain the city’s annual number of days with each type of extreme event. An integrated index was then derived by calculating the equally weighted arithmetic mean of the number of days for each of the four types of extreme events.

$$CPRI_{c,t} = \frac{1}{4}(LTD_{c,t}^{raw} + HTD_{c,t}^{raw} + ERD_{c,t}^{raw} + EDD_{c,t}^{raw}) \quad (2)$$

Here, c represents a city, t represents a year, and the superscript “raw” denotes the cumulative number of days exceeding the threshold for extreme events at the city level. The higher the CPRI value, the greater the climate risk.

Control variables. Based on the studies cited in (Huang and Cheng ., 2024;Liu and Ji ., 2024;Zhang et al., 2025); these include four levels: individual, family, society, and urban.Household level: per capita household consumption (log-transformed), household size, and number of living children. Societal level: whether the household receives old-age pension benefits and whether it participates in health insurance.

Urban level: average wind speed per capita and average hours of sunshine per day. The descriptive statistics for the variables are presented in Table 2.

Table2 Descriptive Statistics (N = 43 228)

Variable	Sample Value	Mean	Standard Deviation	Minimum	Maximum
Health of Middle-Aged and Older Adults	43228	0.245	0.140	0.011	0.998
Number of Days with Extreme Heat	43228	45.829	13.075	11.712	74.775
Extreme Weather Risks	43228	27.542	6.870	11.205	70.756
Age	43228	61.314	9.221	45.000	98.000
Household Registration (rural = 1)	43228	0.781	0.414	0.000	1.000
Marital Status (married = 1)	43228	0.874	0.332	0.000	1.000
Household Size	43228	3.136	1.615	1.000	16.000
Number of Living Children	43228	2.610	1.325	0.000	11.000
Per Capita Household Expenditure (logarithm)）	43228	8.804	1.441	0.000	13.653
Whether the Individual Has Pension Insurance	43228	0.529	0.499	0.000	1.000
Whether the Individual Has Health Insurance	43228	0.953	0.212	0.000	1.000
Average Wind Speed	43228	2.214	0.660	0.921	4.150
Average Hours of Sunshine Per Day	43228	5.085	0.264	4.424	5.643

4 Analysis of Empirical Results

4.1 Benchmark Regression Results

Baseline two-way fixed-effects estimates are presented in Table 3. Column (1) only includes individual and year fixed effects; the coefficient for extreme-weather

risk is −0.002 ($p<0.01$). Columns (2)-(5) sequentially add individual-, household-, social-security- and city-level control variables. The coefficient for extreme-weather risk remains stable at −0.002 and is significant at the 1 % statistical level in all specifications. Higher extreme-climate risk significantly reduces composite health among middle-aged and older adults. Hypothesis 1 receives empirical support.

Table 3 Results of the baseline regression analyzing the impact of extreme weather risks on the health of middle-aged and older adults

Variable	(1)Health of Middle-Aged and Older Adults	(2)Health of Middle-Aged and Older Adults	(3)Health of Middle-Aged and Older Adults	(4)Health of Middle-Aged and Older Adults	(5)Health of Middle-Aged and Older Adults
Extreme Weather Risks	-0.002***	-0.002***	-0.002***	-0.002***	-0.002***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Household Registration		0.000	0.000	0.000	0.003
		(0.005)	(0.005)	(0.005)	(0.005)
Marital Status		-0.000	-0.001	-0.001	-0.001
		(0.005)	(0.005)	(0.005)	(0.005)
Household Size			0.001	0.001	0.000
			(0.001)	(0.001)	(0.001)
Number of Living Children			0.000	0.000	0.000
			(0.001)	(0.001)	(0.001)
Per Capita Household Expenditure (logarithm)			0.001*	0.001	0.001
			(0.001)	(0.001)	(0.001)
Pension Insurance Coverage				0.003	0.002
				(0.002)	(0.002)
Health Insurance Coverage				0.010***	0.010***
				(0.003)	(0.003)
Average Wind Speed					-0.023***
					(0.003)
Average Hours of Sunshine Per Day					0.077***
					(0.008)
Constant	0.291***	0.291***	0.280***	0.270***	-0.063
	(0.004)	(0.007)	(0.009)	(0.010)	(0.041)
Individual fixed-effects	Yes	Yes	Yes	Yes	Yes

Year fixed-effects	Yes	Yes	Yes	Yes	Yes
Observations	43228	43228	43228	43228	43228
R-squared	0.537	0.537	0.537	0.537	0.539

Note: ***, **, and * denote significance levels of 1%, 5%, and 10%, respectively; the numbers in parentheses represent robust standard errors; the same applies to the table below.

4.2 Endogeneity Test

To address potential endogeneity issues in the model, such as omitted variables and bidirectional causality, this paper employs two-stage least squares (2SLS) with instrumental variables for the regression analysis.First,following Lewbel (1997) and Qiu et al. (2026),we construct instrumental variables by taking the cube of the within-group mean of extreme climate risks.The regression results for the first and second stages are presented in columns (1) and (2), respectively, of Table 4. The results show that the Kleibergen-Paap rk Wald F-statistic is 263.586, which is far greater than 10; thus, the model rejects the weak instrumental variable hypothesis. The Kleibergen-Paap rk LM statistic is 207.652, which passes the instrumental variable identifiability test. In the second-stage regression, the regression coefficient for extreme weather risk is $-0.003(p<0.01)$, which is significant at the 1% level, indicating that the results are robust.

Second, to further enhance the rigor of the endogeneity test, this paper selects terrain undulation (Liu and Xia ., 2023;Huang and Wang ., 2026)and slope (Hu and Ma ., 2023;Dong ., 2026) as external instrumental variables.Topographic relief and slope are the core inherent geographic conditions that shape regional microclimates. In areas with greater topographic relief and steeper slopes, airflow and precipitation are less stable, and the probability of climate-related disasters—such as extreme heat and extreme precipitation—is higher. These factors are highly correlated with extreme climate risks and thus meet the correlation requirements for instrumental variables; Topographic ruggedness and slope are inherent natural geographic characteristics of cities and are typical exogenous variables that are not influenced by individual residents' health status, thereby satisfying the exogeneity assumption for instrumental variables. Since these two geographic indicators are virtually constant variables, their inclusion in a two-way fixed-effects model would result in their complete absorption; therefore, this study incorporates the interaction terms between topographic ruggedness and year, as well as between the reciprocal of slope and extreme climate risk values, into the regression model. The regression results are presented in Table 4, columns (3) through (6). For the terrain ruggedness instrumental variable, the Kleibergen-Paap rk LM statistic is 299.687, and the Kleibergen-Paap rk Wald F statistic is 456.818; for the slope instrumental variable, the Kleibergen-Paap rk LM statistic was 1,895.772 and the Kleibergen-Paap rk Wald F statistic was 4,792.353. Both sets of results passed the under-identification test and the weak instrumental variable test, confirming the validity of the instrumental variables

selected. The results of the second-stage regression show that the extreme climate risk coefficients corresponding to the two types of instrumental variables are -0.007 and -0.003, respectively, both significantly negative at the 1% level. This demonstrates that extreme climate risk has a significant inhibitory effect on the health of middle-aged and older adults, confirming that the core research conclusions of this paper are robust and reliable.

Table 4 Results of the Endogeneity Test

Variable	（1）First-stage regression	（2）Second-stage regression	（3）First-stage regression	（4）Second-stage regression	（5）First-stage regression	（6）Second-stage regression
Instrumental Variables	0.001*** (0.000)		0.196*** (0.009)		3.886*** (0.056)	
Extreme Climate Risks		-0.003*** (0.000)		-0.007*** (0.001)		-0.003*** (0.000)
Control Variables	Yes	Yes	Yes	Yes	Yes	Yes
Individual fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	43228	43228	43228	43228	43228	43228
Kleibergen-Paap rk LM	207.652		299.687		1895.772	
Kleibergen-Paap rk Wald F	263.586		456.818		4792.353	

4.3 Robustness Tests

4.3.1 Propensity Score Matching

To minimize the impact of self-selection bias in the sample on the empirical results, this paper employs the propensity score matching method to conduct robustness tests. Table 5 reports the results of the propensity score matching tests; the coefficient for extreme weather risk in column (1) is -0.002, which is significantly negative at the 1% significance level, indicating that the core findings of this paper are reliable.

Table 5 Results of the Propensity Score Matching Test

Variable	(1)Nearest Neighbor Matching
Extreme Climate Risks	-0.002*** (0.000)

Constant	-0.003 (0.058)
Control Variables	Yes
Individual fixed-effects	Yes
Year fixed-effects	Yes
Observations	21482
R-squared	0.574

4.3.2 Dual Machine Learning Models

To relax the linearity assumption, avoid model specification bias, and more accurately infer the causal relationship between extreme weather risks and the health of middle-aged and older adults, this study will conduct a new regression analysis using a dual machine learning model, following the research approach outlined in (Chernozhukov et al.,2018). Table 6 reports the results of the dual machine learning model analysis. In column (1), the coefficient for extreme climate risk is −0.0021, which is significantly negative at the 1% statistical level. Extreme climate risk continues to significantly reduce the health status of middle-aged and older adults, indicating that the core conclusion is highly robust and reliable.

Table 6 Results of the Dual Machine Learning Model Test

Variable	(1)Dual Machine Learning Models
Extreme Climate Risks	-0.0021***
	(0.0001)
First-order term of the control variable	Yes
Second-order term of the control variable	Yes
Individual fixed-effects	Yes
Year fixed-effects	Yes
Observations	43228

4.3.3 Controlling for the Impact of the Pandemic

The COVID-19 pandemic in 2020 exerted a strong exogenous shock on residents' physical and mental health, daily routines, and the supply of medical resources, which could easily lead to observational bias in the sample and interfere with the identification of core effects. To address this, this paper excluded the 2020 annual sample and re-conducted the regression analysis. Column (1) of Table 7 shows that the regression coefficient for extreme weather risks is significantly negative at the 1% significance level, and the core conclusion remains robust.

4.3.4 Scope of Sample Replacement

Given that the four municipalities directly under the central government—Beijing, Shanghai, Tianjin, and Chongqing—differ significantly from typical prefecture-level cities in terms of economic development, public healthcare resources, urban governance systems, and climate resilience, the unique characteristics of the sample could introduce estimation bias. Therefore, this study excludes these four

municipalities from the sample and performs the regression analysis again. As shown in Table 7, column (2), the extreme climate risk coefficient is significantly negative at the 1% significance level, indicating that the core findings are not distorted by the inclusion of these unique cities in the sample.

4.3.5 Substituting Interpreted Variables

To avoid the randomness in conclusions caused by measurement biases in single health indicators, this paper uses the Relative Deprivation Index to reconstruct a comprehensive health indicator for middle-aged and older adults. Kakwani (1984) points out that the lower the Relative Deprivation Index, the smaller the health disparities among older adults and the greater the relative equity in health status. The specific calculation method is as follows: Let X = (x_1, x_2, x_3, ⋯, x_k) be a vector of group health scores of size k, where $x_1 \leqslant x_2 \leqslant x_3 \leqslant \cdots \leqslant$ x_(k−1) $\leqslant$ x_k. After arranging all samples within the group in ascending order of health scores, individual i is compared with all reference individuals j whose health scores are higher than its own. The relative deprivation index can be expressed as:

$$D(x_j, x_i) = \begin{cases} x_j - x_i, x_j > x_i \\ 0, x_j \leqslant x_i \end{cases} \quad (3)$$

Based on this, the average health relative deprivation index for individual i is:

$$RD(x_i) = \frac{1}{k\mu_x}[\sum_{j=i+1}^{k}(x_j - x_i)] = \gamma_{x_i}^{+} + [\frac{(\mu_{x_i}^{+} - x_i)}{\mu_x}] \quad (4)$$

Column (3) of Table 7 shows that the extreme weather risk coefficient is highly significant and positive at the 1% level, indicating that extreme weather risks exacerbate health inequalities among middle-aged and older adults. The conclusions of this study do not depend on specific methods of variable measurement, and the results demonstrate good robustness.

4.3.6 Two-Sided Truncation

To eliminate the interference of extreme outliers on the regression results, this study performed two-sided truncation (1–99) on all continuous variables and conducted the regression analysis again. Column (4) of Table 7 shows that the extreme climate risk coefficient is significantly negative, which is highly consistent with the baseline results; thus, the core conclusions are not affected by extreme values in the sample.

4.3.7 Adding Control Variables

To further mitigate potential omitted variable bias in the model and precisely isolate the impact of differences in individual employment status on health, this study adds “retirement status” to the existing set of control variables. Column (5) of Table 7 shows that the extreme climate risk coefficient is significantly negative at the 1% level, confirming the reliability of the baseline regression results.

4.3.8 Adjusting for Fixed Effects

To address the limitations in the basic two-way fixed-effects model, this study adds additional fixed effects. By incorporating city-level fixed effects, we control for city-level characteristics that do not vary over time, thereby addressing the identification shortcomings associated with controlling only for individual and year fixed effects. Column (6) of Table 7 shows that the risk coefficients for extreme

weather are all significantly negative, and the core conclusions remain robust.

Table 7 Results of Robustness Tests

Variable	(1)Controlling for the Impact of the Pandemic	(2)Scope of Sample Replacement	(3)Substituting Interpreted Variables	(4)Two-Sided Truncation	(5)Adding Control Variables	(6)Adjusting for Fixed Effects
Extreme Climate Risks	-0.001*** (0.000)	-0.002*** (0.000)	0.000*** (0.000)	-0.002*** (0.000)	-0.002*** (0.000)	-0.002*** (0.000)
Constant	0.060 (0.048)	-0.040 (0.041)	0.237*** (0.038)	-0.033 (0.040)	-0.067* (0.041)	-0.063 (0.041)
Control Variables	Yes	Yes	Yes	Yes	Yes	Yes
Individual fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes
Retire	No	No	No	No	Yes	No
City fixed-effects	No	No	No	No	No	Yes
Observations	32846	41959	43228	43228	43228	43228
R-squared	0.568	0.537	0.598	0.544	0.539	0.539

4.4 Testing of Mediating Mechanisms

Based on the theoretical analysis presented earlier, Tables 8–10 further report the results of tests examining the mechanisms through which extreme climate risks affect the health of middle-aged and older adults.

4.4.1 Increased Burden of Caring for Grandchildren

To examine the transmission channels through which extreme weather risks affect the health of middle-aged and older adults, this study—taking into account the availability of variables in the CHARLS survey and meteorological data—selected the indicators "whether they care for grandchildren" (SF1), "whether they have children and their spouses living in the same city" (SF2), and "whether they live with their children" (SF3) to measure the burden of caring for grandchildren. The regression results are shown in Table 8. Extreme weather risks significantly increase caregiving behaviors among middle-aged and older adults, exacerbating intergenerational time crowding. After including mediating variables, the three types of intergenerational caregiving behaviors were found to have a significant negative impact on the health of middle-aged and older adults, and the negative core effect of extreme weather risks was significant. This indicates that the reorganization of

intergenerational time resources plays a partial mediating role between the two, meaning that extreme weather risks further erode the physical and mental health of middle-aged and older adults by increasing their burden of caring for grandchildren and crowding out personal rest time. A possible reason is that frequent extreme weather events lead to a deterioration of the local living environment, increased travel risks, and reduced stability in daily life. Under pressure from external environmental factors and life demands, young adult children tend to shift more of the responsibility for family care and grandchild care onto middle-aged and older adults. The time middle-aged and older adults would otherwise devote to leisure, wellness, sleep regulation, and mental and physical relaxation is significantly encroached upon. Long-term, persistent caregiving pressures can lead to physical and mental exhaustion, emotional anxiety, and disrupted sleep patterns, ultimately having a significant negative impact on their physical and mental health.

Table 8 Results of the Test on the Mechanism of the Grandchildren's Caregiving Burden

Variable	（1） SF1	（2） Health of Middle-Aged and Older Adults	（3） SF2	（4） Health of Middle-Aged and Older Adults	（5） SF3	（6） Health of Middle-Aged and Older Adults
Extreme Weather Risks	0.002***	-0.002***	0.001*	-0.002***	0.002***	-0.002***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
SF1		-0.052***				
		(0.003)				
SF2				-0.032***		
				(0.002)		
SF3						-0.024***
						(0.002)
Constant	0.737***	-0.025	1.329***	-0.021	0.929***	-0.040
	(0.117)	(0.040)	(0.114)	(0.040)	(0.133)	(0.040)
Control Variables	Yes	Yes	Yes	Yes	Yes	Yes
Individual fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	43228	43228	43228	43228	43228	43228
R-squared	0.720	0.549	0.642	0.543	0.613	0.542

4.4.2 Reduction in Upward Economic Support

To further examine the mediating effect of intergenerational support, this study selected the indicators “Whether any financial assistance was received from children in the past year” (JC1) and “Amount of financial assistance received from children in the past year” (JC2) to measure upward economic support, based on the availability of variables in the CHARLS survey and meteorological data. The regression results are presented in Table 9. Extreme weather risks significantly suppress both the behavior and scale of upward economic support provided by children to middle-aged and older adults. After incorporating mediating variables, intergenerational economic support was found to significantly improve the health status of middle-aged and older adults, while the negative health effects of extreme weather risks were also significant. This indicates that the redistribution of intergenerational economic resources plays a partial mediating role between the two; that is, extreme weather risks harm the health of middle-aged and older adults by reducing intergenerational economic support and weakening their ability to withstand risks. A possible reason is that frequent extreme weather events disrupt regional production and daily life, driving up daily living expenses, disaster prevention and risk mitigation costs, and expenditures related to property damage, thereby increasing the economic burden and life pressures on young adult children. To cope with the economic uncertainty caused by extreme weather, children may proactively reduce financial support for their middle-aged and elderly parents, such as maintenance allowances and living subsidies. Middle-aged and older adults have limited sources of income and weak economic resilience; they rely heavily on financial support from their children to maintain high-quality health and wellness conditions and access medical resources. The weakening of intergenerational economic support makes it difficult for middle-aged and older adults to effectively offset the lifestyle losses and health impacts caused by extreme weather. Insufficient investment in health and wellness resources and a decline in risk resilience ultimately lead to a deterioration in their physical and mental health.

Table 9 Test Results for the Upward Economic Support Mechanism

Variable	(1) JC1	(2) Health of Middle-Aged and Older Adults	(3) JC2	(4) Health of Middle-Aged and Older Adults
Extreme Weather Risks	-0.002***	-0.001***	-0.004**	-0.002***
	(0.000)	(0.000)	(0.002)	(0.000)
JC1		0.325***		
		(0.010)		
JC2				0.037***
				(0.001)
Constant	-0.528***	0.109***	-2.443***	0.027
	(0.062)	(0.035)	(0.550)	(0.035)
Control Variables	Yes	Yes	Yes	Yes

Individual fixed-effects	Yes	Yes	Yes	Yes
Year fixed-effects	Yes	Yes	Yes	Yes
Observations	43228	43228	43228	43228
R-squared	0.544	0.640	0.429	0.648

4.4.3 Weakening Intergenerational Emotional Interaction

Based on the availability of variables in the CHARLS survey and meteorological data, this study selected the following indicators: “Whether they have face-to-face contact with their children weekly” (DQ1), “Whether they contact their children weekly by phone, text message, mail, or email” (DQ2), “Whether they contact any of their children weekly in person or by phone, text message, mail, or email” (DQ3), “satisfaction with the parent-child relationship (DQ4)” to measure intergenerational emotional interaction. The regression results are shown in Table 10. Extreme weather risks significantly suppress various forms of intergenerational emotional interaction among middle-aged and older adults, as well as their satisfaction with the parent-child relationship, thereby weakening emotional bonds within the family. After controlling for mediating variables, positive intergenerational emotional interaction and high-quality parent-child relationships were found to significantly improve the health status of middle-aged and older adults, while the negative health effects of extreme climate risks were significant. This indicates that the reorganization of intergenerational emotional resources plays a partial mediating role between the two, meaning that extreme climate risks further harm the physical and mental health of middle-aged and older adults by weakening intergenerational emotional companionship and eroding emotional support within the family. A possible reason is that frequent extreme weather events disrupt regional transportation and daily life routines, thereby reducing the opportunities and frequency of face-to-face communication and interaction among family members. At the same time, the environmental anxiety, life uncertainty, and disaster preparedness pressures caused by extreme weather are likely to trigger emotional fluctuations among family members, reducing their willingness to communicate with their children and weakening emotional bonds. The mental health of middle-aged and older adults is highly dependent on emotional support from their families. The continued weakening of intergenerational emotional interactions exacerbates negative emotions such as loneliness and anxiety. The long-term accumulation of psychological stress further undermines their physical health, ultimately leading to a dual decline in both their mental and physical well-being.

Table 10 Results of the Test on the Mechanisms of Intergenerational Emotional Interaction

Variable	(1) DQ1	(2) Health of Middle-Aged and Older Adults	(3) DQ1	(4) Health of Middle-Aged and Older Adults	(5) DQ1	(6) Health of Middle-Aged and Older Adults	(7) DQ1	(8) Health of Middle-Aged and Older Adults
Extreme Weather Risks	-0.002*** (0.000)	-0.002*** (0.000)	-0.001*** (0.000)	-0.002*** (0.000)	-0.001*** (0.000)	-0.002*** (0.000)	-0.001* (0.001)	-0.002*** (0.000)
DQ1		0.203*** (0.006)						
DQ2				0.017*** (0.002)				
DQ3						0.036*** (0.002)		
DQ4								0.015*** (0.001)
Constant	-0.491*** (0.079)	0.037 (0.036)	0.680*** (0.138)	-0.074* (0.041)	0.925*** (0.119)	-0.096** (0.040)	2.959*** (0.249)	-0.107*** (0.041)
Control Variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individual fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	43228	43228	43228	43228	43228	43228	43228	43228
R-squared	0.472	0.606	0.605	0.541	0.436	0.543	0.611	0.543

4.5 Heterogeneity Test

The results of the benchmark regression, endogeneity test, and multiple robustness tests discussed earlier consistently indicate that extreme weather risks significantly reduce the health status of middle-aged and older adults. To further systematically investigate the differential impacts across different subgroups, this study examines the heterogeneity in the effects of extreme weather risks on the health

status of middle-aged and older adults with different characteristics across three dimensions: individual demographic characteristics (gender), socioeconomic characteristics (per capita household income and educational attainment), and geographic regional characteristics.

4.5.1 Gender

In this study, the sample was divided into two groups—male and female—based on gender, and group-specific regression analyses were conducted. Columns (1) and (2) of Table 11 show that the extreme climate risk coefficients for both the male and female groups are -0.002, which are significantly negative at the 1% level. This indicates that extreme climate risks have a significant adverse impact on the health of both men and women; regardless of gender, health levels are significantly suppressed by the detrimental effects of extreme climate events, and heterogeneity across the gender dimension is relatively weak.

4.5.2 Per Capita Household Income

Household economic status serves as a crucial foundation for residents' ability to withstand climate risks and access health care resources, and may lead to differential health effects from extreme climate risks. Therefore, this study divides the sample into low-income and high-income groups based on the median per capita household income and conducts group-specific regression analyses. Columns (3) and (4) of Table 11 show that the extreme climate risk coefficient for the low-income group is −0.002, which is significantly negative at the 1% level; for the high-income group, the extreme climate risk coefficient is −0.003, which is also significantly negative at the 1% level. This indicates that middle-aged and older adults in the high-income group experience a stronger negative impact from extreme weather. A possible reason is that the high-income group generally possesses better baseline health and a higher quality of living environment, making them more sensitive to environmental disturbances and disruptions to daily life caused by extreme weather; in contrast, the low-income group has long lived in relatively harsh living conditions and has developed greater resilience to climate fluctuations, resulting in a relatively weaker health-detrimental effect from extreme weather.

Table 11 Results of the Analysis of Gender and Per Capita Household Income

Variable	（1）Men	（2）Women	（3）Low-income group	（4）High-income group
Extreme Climate Risks	-0.002***	-0.002***	-0.002***	-0.003***
	(0.000)	(0.000)	(0.000)	(0.000)
Constant	-0.056	-0.072	0.041	-0.259***
	(0.060)	(0.055)	(0.057)	(0.073)
Control Variables	Yes	Yes	Yes	Yes
Individual fixed-effects	Yes	Yes	Yes	Yes
Year fixed-effects	Yes	Yes	Yes	Yes

Observations	20842	22386	17855	17859
R-squared	0.543	0.534	0.546	0.573

4.5.3 Educational Attainment

An individual’s level of education can influence health literacy, risk-prevention behaviors, and health management capabilities, making it a key determinant of climate-related health effects. In this study, the sample was divided into four groups based on educational attainment—elementary school or below, junior high school, high school, and bachelor’s degree or higher—for group-specific regression analysis. Columns (1) through (4) of Table 12 show that the extreme climate risk coefficients for the “elementary school and below” and “junior high school” groups were both -0.001, both significantly negative at the 1% level; whereas the coefficients for the “high school” and “bachelor’s degree and above” groups were both -0.003, both significantly negative at the 1% level. This indicates that as the educational attainment of middle-aged and older adults increases, the negative impact of extreme climate risks on their health tends to rise. A possible reason lies in the fact that, from the perspective of health expectations, groups with higher incomes and educational attainment possess greater health literacy and stricter standards for evaluating health. Relative deprivation theory suggests that an individual’s assessment of their own condition depends not only on absolute levels but also on the gap between their current state and their expected reference point. When extreme weather events disrupt their daily health equilibrium, the same degree of objective health impairment can lead to a greater subjective health gap and psychological anxiety. From the perspective of occupational structure, high-income groups are more likely to be engaged in intellectual labor and the service sector; these occupations place higher demands on cognitive function and emotional stability and are more sensitive to high-temperature environments. The decline in cognitive function and loss of work efficiency caused by extreme heat translate into higher opportunity costs and more significant physical and mental strain for these groups. From a lifestyle perspective, high-income, highly educated groups engage in a wider range of outdoor recreational and social activities; extreme heat directly limits the feasibility of these health-promoting activities. In contrast, low-income groups, who have long lived in relatively harsh living conditions, have a higher adaptation threshold to climate fluctuations, and the marginal health damage caused by extreme weather is actually smaller for them.

Table 12 Results of the Test for Heterogeneity in Educational Attainment

Variable	（1）Elementary school and below	（2）Middle school	（3）High school	（4）Bachelor's degree and above
Extreme Climate Risks	-0.001***	-0.001***	-0.003***	-0.003***
	(0.000)	(0.000)	(0.000)	(0.000)
Constant	-0.019	0.033	-0.145	-0.168
	(0.057)	(0.084)	(0.094)	(0.127)
Control Variables	Yes	Yes	Yes	Yes

Individual fixed-effects	Yes	Yes	Yes	Yes
Year fixed-effects	Yes	Yes	Yes	Yes
Observations	19248	9748	8926	5306
R-squared	0.500	0.506	0.528	0.558

4.5.4 Geographic Regions

There are significant differences across China’s various regions in terms of climatic characteristics, levels of economic development, ecological environments, and disaster prevention and mitigation capabilities; consequently, the health impacts of extreme weather events may vary by region. To this end, this paper first divides the sample into the Yangtze River Economic Belt and non-Yangtze River Economic Belt regions, and then conducts further analysis by the three major regions: the eastern, central, and western regions. Columns (1) through (5) of Table 13 show that, on the one hand, from a river basin perspective, the extreme weather risk coefficient for the Yangtze River Economic Belt is -0.001, while that for the non-Yangtze River Economic Belt sample is -0.003; both are significantly negative at the 1% level, indicating that older adults in the non-Yangtze River Economic Belt experience a stronger health impact from extreme weather. On the other hand, from the perspective of the three major regions, the coefficient for the eastern region was -0.003 and that for the central region was -0.002, both of which were significantly negative; the coefficient for the western region was close to 0 and did not pass the statistical significance test. Geographic heterogeneity indicates that the health-damaging effects of extreme weather are primarily concentrated in the central and eastern regions, as well as in areas outside the Yangtze River Economic Belt. The reasons for this are as follows: the eastern region is densely populated and highly urbanized, making it particularly susceptible to fluctuations in the urban ecosystem and living environment triggered by extreme weather, which in turn have a significant impact on residents’ health; the central region, having absorbed industrial relocation from the east, has relatively weak climate adaptability and disaster prevention infrastructure, resulting in pronounced negative health effects from climate risks; whereas the western region, with its lower population density, relatively low intensity of human activity, and vast geographical expanse—which provides greater buffering capacity against localized extreme weather—experiences no significant adverse effects of extreme weather on the health of middle-aged and elderly residents.

Table 13 Results of the Test for Geographic Heterogeneity

Variable	(1) Yangtze River Economic Belt	(2) Non-Yangtze River Economic Belt	（3） Eastern Region	（4） Central Region	（5） Western Region
Extreme Climate Risks	-0.001*** (0.000)	-0.003*** (0.000)	-0.003*** (0.000)	-0.002*** (0.000)	-0.000 (0.000)
Constant	-0.316***	0.255***	-0.043	0.234***	-0.465***

	(0.078)	(0.056)	(0.075)	(0.060)	(0.087)
Control Variables	Yes	Yes	Yes	Yes	Yes
Individual fixed-effects	Yes	Yes	Yes	Yes	Yes
Year fixed-effects	Yes	Yes	Yes	Yes	Yes
Observations	19404	23824	15906	14134	13188
R-squared	0.543	0.540	0.536	0.534	0.577

5 Further Analysis: Extreme heat and climate-innovation-patent mechanisms

As global average temperatures rise, the frequency of heatwaves is increasing and spreading to wider geographic areas, with far-reaching implications for human activities, ecosystems, and economic activities (Song et al.,2026;Zheng et al.,2023;Miller et al.,2021).Against this backdrop, the hidden toll of extreme heat on residents' health continues to intensify. Previous studies have confirmed that extreme climate risks significantly impair the health of middle-aged and older adults, with multidimensional heterogeneity observed across different population groups and regions. To deepen the research, this paper focuses on extreme heat to examine its specific impact on the health of middle-aged and older adults. By constructing a mediating mechanism based on the dual dimensions of mitigation and adaptation-oriented climate innovation patents, this study clarifies the transmission pathways through which extreme heat affects the health of middle-aged and older adults, thereby enriching the micro-level empirical evidence on the health effects of extreme climate events.

5.1 Testing the Specific Effects of Extreme Heat

Extreme heat can not only disrupt the body's physiological homeostasis and exacerbate chronic diseases, but also harm residents' physical and mental health by disrupting daily routines and limiting outdoor activities. Accordingly, this study conducts a regression analysis using the number of extreme heat days as the core explanatory variable. Table 14 reports the results of the specific effects test for extreme heat. Column (1) presents the baseline results, controlling only for individual and year fixed effects; the coefficient for the number of extreme heat days is significantly negative at the 1% significance level. In Column (2), after incorporating control variables, the number of extreme heat days continues to significantly suppress the health status of middle-aged and older adults. Possible reasons include the relatively weak physiological regulatory capacity and lower heat tolerance among middle-aged and older adults. Prolonged periods of extreme heat can increase the risk of chronic diseases such as cardiovascular and respiratory conditions. At the same time, high temperatures limit outdoor physical activity and reduce sleep quality, ultimately exerting a negative impact on physical and mental health. These findings reinforce the core conclusion of this paper, demonstrating that extreme heat is a significant contributing factor to the adverse health effects of extreme climate risks on middle-aged and older adults.

Table 14 Results of the Specific Effects Test for Extreme Heat Events

Variable	（1）Health of Middle-Aged and Older Adults	（2）Health of Middle-Aged and Older Adults
Number of Days with Extreme Heat	-0.000***	-0.000***
	(0.000)	(0.000)
Constant	0.259***	0.038
	(0.003)	(0.042)
Control Variables	No	Yes
Individual fixed-effects	Yes	Yes
Year fixed-effects	Yes	Yes
Observations	43228	43228
R-squared	0.536	0.537

5.2 Testing the Mediating Mechanism of Climate Innovation Patents

To further elucidate the mechanisms through which extreme heat affects the health of middle-aged and older adults, drawing on the approach outlined in (Long and Wang ., 2025), this study distinguishes between two categories of climate innovation technologies—mitigation patents and adaptation patents—from the perspective of climate technology innovation. We construct a mediation model to test whether extreme heat affects the health of middle-aged and older adults by influencing the level of climate innovation. Table 15 reports the results of the mediation analysis for climate innovation patents. Column (1) shows that the coefficient for the number of extreme heat days is significantly positive at the 1% level, indicating that extreme heat shocks can effectively drive the upgrading of regional climate mitigation technology innovation. The results in Column (2) indicate that mitigation patents significantly improve the health levels of middle-aged and older adults, while the negative health effects of extreme heat remain significant. This demonstrates that mitigation patents play a partial mediating role: extreme heat can mitigate its negative impact on the health of middle-aged and older adults by incentivizing technological innovation in climate governance, thereby establishing a positive buffering mechanism where “risk drives innovation, and innovation offsets health losses.”

Column (3) shows that extreme heat significantly suppresses the output of adaptive patent R&D. The reason for this is that intense extreme heat events crowd out regional innovation resources, increase R&D uncertainty, and hinder the iteration and upgrading of climate-adaptive technologies. The results in Column (4) indicate that adaptation-related patents can significantly improve the health of middle-aged and older adults. Thus, extreme heat can weaken regional disaster resilience by inhibiting climate adaptation innovation, thereby further exacerbating health deterioration among middle-aged and older adults and forming a negative mediating pathway.

Table 15 Results of the Test of the Climate Innovation Patent Intermediation

Mechanism

Variable	(1) Mitigation Patents	(2) Health of Middle-Aged and Older Adults	(3) Adaptation Patents	(4) Health of Middle-Aged and Older Adults
Number of Days with Extreme Heat	0.015***	-0.001***	-0.032***	-0.000***
	(0.002)	(0.000)	(0.009)	(0.000)
Mitigation Patents		0.005***		
		(0.000)		
Adaptation Patents				0.001***
				(0.000)
Constant	12.295***	-0.095***	-20.014***	-0.019
	(1.346)	(0.042)	(5.427)	(0.041)
Control Variables	Yes	Yes	Yes	Yes
Individual fixed-effects	Yes	Yes	Yes	Yes
Year fixed-effects	Yes	Yes	Yes	Yes
Observations	43228	43228	43228	43228
R-squared	0.811	0.544	0.350	0.545

6 Discussion

Drawing on five-wave CHARLS panel data merged with prefecture-level meteorological records, this paper finds that composite extreme-climate risks significantly worsen multi-dimensional health outcomes for Chinese middle-aged and older adults. Beyond documenting total health effects, this study unpacks family-intergenerational-support social transmission channels largely neglected in prior climate-health quantitative literature. Extreme-weather hazards reshape three core dimensions of Chinese family intergenerational exchange: raising grandchild-care burdens, compressing upward financial transfers from adult children, and eroding intergenerational emotional companionship. Each channel partially mediates climate-risk-driven health deterioration. This highlights that climate-health harms are not limited to direct physiological exposure; household-family relational dynamics represent critical intermediate social pathways translating environmental shocks into individual-level health outcomes.

Heterogeneity tests reveal nuanced subgroup patterns. Counter-intuitively, higher-income and higher-education subgroups suffer larger marginal health damages under extreme-climate risk. This does not mean their absolute health vulnerability is greater; rather it reflects divergent reference frames, lifestyles and occupational sensitivity. Socio-economically disadvantaged older adults endure substantial structural-health disadvantages overall yet display comparatively muted marginal sensitivity to additional climate-hazard perturbations. Geographically, central-eastern China bears the main burden of climate-risk-related health harms, while western-region coefficients are non-significant, pointing to the importance of population density,

urban-industrial contexts and adaptive-infrastructure stocks.

When isolating extreme heat, divergent mediating roles emerge for mitigation- versus adaptation-oriented climate-innovation patents. Heat hazards incentivise mitigation-technology innovation that buffers health losses; simultaneously, extreme heat suppresses adaptive-patent R&D and aggravates health deterioration. This differentiated technological-innovation pathway adds new micro-level empirical evidence linking regional green-technology development to elderly-population health outcomes.

Limitations

This study has several notable limitations. First, we rely on prefecture-city-aggregated meteorological proxies rather than granular real-time individual-level weather exposure, generating potential measurement error. Second, intergenerational-support mediators are constructed using available CHARLS survey items and cannot capture every nuance of family-relational shifts triggered by climate shocks. Third, patent data measure regional-level innovation outputs instead of actual on-the-ground community-technology penetration rates. Fourth, notwithstanding the deployment of instrumental-variable strategies to address endogeneity, unobservable time-varying confounders cannot be completely eliminated. Future mixed-methods qualitative research could explore lived household-family experiences during extreme-weather episodes; subsequent work might also evaluate how community-elder-care services modify the intergenerational-support mediating pathways identified in this paper.

Conclusions

Based on five-wave 2011-2020 CHARLS data merged with prefecture-level meteorological unbalanced-panel data (43 228 observations), this paper demonstrates that extreme-climate risks significantly worsen multi-dimensional health status for China’s middle-aged and older adults. Three intergenerational-support mechanisms transmit environmental-shock-related health harms: heavier grandchild-care responsibilities, diminished upward economic transfers from adult children, and weakened intergenerational emotional interactions. Health impacts exhibit systematic heterogeneity across socioeconomic subgroups and geographic zones. Extreme heat represents a principal driver of climate-related health deterioration; mitigation-type climate-innovation patents partially offset heat-related health losses, while suppressed adaptive-technology patents amplify adverse health consequences.

First, establish a targeted protection system for extreme weather to strengthen climate health defenses for middle-aged and older adults. Local meteorological and health authorities should establish a coordinated early warning mechanism linking extreme climate events and extreme heat to health risks, issue specialized health guidelines for hazardous weather conditions such as high temperatures and extreme temperature fluctuations, and prioritize improving heat relief services for the elderly,

grassroots medical outreach, and emergency rescue systems during periods of extreme heat. Focusing on climate-sensitive regions such as the central and eastern parts of the country and areas outside the Yangtze River Economic Belt, investment in grassroots elderly care, medical services, and emergency shelter facilities should be increased. Relying on community day care centers and wellness stations, routine climate-adapted elderly care services should be provided to precisely mitigate the direct health impacts of extreme weather on middle-aged and older adults.

Second, optimize the structure of intergenerational family support to address family resource constraints under climate risks. At the public level, vigorously develop universal childcare and community care services to alleviate the burden of caring for grandchildren on families, prevent the excessive shifting of caregiving responsibilities onto middle-aged and elderly individuals in the context of extreme weather, and ensure they have adequate space for rest, wellness, and mental and physical recovery. At the policy level, improve systems for temporary relief during climate disasters and family-based elder care support; provide special subsidies to families affected by disasters or facing soaring living costs to stabilize children's ability to provide financial support. At the same time, community-based platforms for family interaction should be established to maintain strong intergenerational emotional bonds and alleviate the negative psychological effects triggered by extreme weather.

Third, implement a differentiated and targeted governance model to narrow climate health disparities among different groups and across regions. For climate-sensitive groups—such as those with high incomes and high levels of education—strengthen public health education and psychological counseling regarding extreme weather, guiding them to adopt adaptive healthy lifestyles and reduce physical and mental anxiety caused by environmental fluctuations. For vulnerable middle-aged and elderly individuals with low incomes, low educational attainment, and those in underdeveloped regions, we will address shortcomings in basic healthcare, elderly care, and disaster-prevention infrastructure to enhance their climate adaptation capacity and risk resilience. Taking into account the differences in climate impacts across the eastern, central, and western regions, we will implement tiered governance strategies tailored to local conditions to ensure the refined and precise implementation of health governance in response to extreme weather.

Fourth, we will deepen the empowerment of climate technology innovation to

establish a long-term climate health governance mechanism. Balance the dual effects of climate innovation: on the one hand, continue to support the research, development, and implementation of mitigation-oriented patented technologies—such as energy conservation, emissions reduction, cooling, disaster mitigation, and environmental governance—to optimize the urban living environment and leverage the health-protective benefits of green innovation; on the other hand, increase support for the research and development of adaptive technologies—including extreme weather early warning systems, disaster-preparedness adaptations, and emergency response measures—to counteract the inhibitory effects of extreme heat on innovation activities and enhance regional climate resilience. To promote the application of climate adaptation technologies in community-based elderly care settings, local governments can incorporate patented products—such as cooling building materials and smart high-temperature early-warning terminals—into aging-in-place renovation projects, deploying them in community day care centers and senior care facilities. By leveraging the virtuous cycle of "climate governance, technological innovation, and health empowerment," we can achieve the coordinated development of ecological governance, technological advancement, and health protection for middle-aged and elderly individuals.

References

Jin Y., Hu W., Feng Y., 2024. Internet use and the life of middle-aged and older adults in the digital era: Analysis of the main findings from the digital divide and digital inclusion survey of Chinese older adults. Population Research 48(1), 40-55.(In Chinese).

United Nations Department of Economic and Social Affairs, Population Division, 2024. World Population Prospects 2024.

State Council of the People's Republic of China, 2026. Outline of the 15th Five-Year Plan. Retrieved from https://www.gov.cn/yaowen/liebiao/202603/content_7062633.html.

Ministry of Ecology and Environment of China, 2022. National Strategy for Adaptation to Climate Change 2035. Retrieved from https://www.mee.gov.cn/xxgk2018/xxgk/xxgk03/202206/t20220613_985261.html.

Wang H., Guo C., Ni T., 2025. Climate change, trade costs and economic growth — Quantitative estimation based on international shipping data. Management World 41(9), 94-118.https://doi.org/10.19744/j.cnki.11-1235/f.2025.0123.(In Chinese).

Ban J., Shi W., Cui L., Liu X., Jiang C., Han L., et al., 2019. Health-risk perception and its mediating effect on protective behavioral adaptation to heat waves. Environmental Research 172, 27-33.https://doi.org/10.1016/j.envres.2019.01.006.

Dimitrova A., Ingole V., Basagaña X., et al., 2021. Association between ambient temperature and heat waves with mortality in South Asia: Systematic review and meta-analysis. Environment International 146, 106170.https://doi.org/10.1016/j.envint.2020.106170.

Tian Y., Zhang S., Luo B., et al., 2013. Research progress on the effects of heat waves on human health. Advances in Meteorological Science and Technology 3(2), 49-54.(In Chinese).

Xi D., Liu L., Zhang M., et al., 2024. Risk factors associated with heatwave mortality in Chinese adults over 65 years. Nature Medicine 30(5), 1489-1498. https://doi.org/10.1038/s41591

Zhang R., Sun L., Jia A., et al., 2024. Effect of heatwaves on mortality of Alzheimer's disease and other dementias among elderly aged 60 years and above in China, 2013-2020: a population-based study. The Lancet Regional Health-Western Pacific 52.https://doi.org/10.1016/j.lanwpc.2024.101217.

Cheng J., Xu Z., Bambrick H., et al., 2018. Heatwave and elderly mortality: An evaluation of death burden and health costs considering short-term mortality displacement. Environment International 115, 334-342.https://doi.org/10.1016/j.envint.2018.03.041.

Hua Y., Qiu Y., Tan X., 2023. The Effects of Temperature on Mental Health: Evidence from China. Journal of Population Economics 36, 1293-1332. https://doi.org/10.1007/s00148.

Dell M., Jones B.F., Olken B.A., 2009. Temperature and income: reconciling new cross-sectional and panel estimates. American Economic Review 99(2), 198-204.https://doi.org/10.3386/w14680.

Hsiang S.M., Burke M., Miguel E., 2013. Quantifying the influence of climate on human conflict. Science 341(6151), 1235367. https://doi.org/10.1126/science.1235367

Ranson M., 2014. Crime, weather, and climate change. Journal of Environmental Economics and Management 67(3), 274-302.https://doi.org/10.1016/j.jeem.2013.11.008.

Carleton T.A., 2017. Crop-damaging temperatures increase suicide rates in India.

Proceedings of the National Academy of Sciences 114(33), 8746-8751. https://doi.org/10.1073/pnas.1701354114.

Obradovich N., Migliorini R., Mednick S.C., et al., 2017. Night-time temperature and human sleep loss in a changing climate. Science Advances 3(5), e1601555. https://doi.org/10.1126/sciadv.1601555.

Obradovich N., Migliorini R., Paulus M.P., et al., 2018. Empirical evidence of mental health risks posed by climate change. Proceedings of the National Academy of Sciences 115(43), 10953-10958.https://doi.org/10.1073/pnas.1801528115.

White C., 2017. The effect of temperature on human mortality in a changing world: a review. Current Environmental Health Reports 4(4), 454-461. https://doi.org/10.1007/s40572.

Karlsson M., Ziebarth N.R., 2018. Population health effects and health-related costs of extreme temperatures: comprehensive evidence from Germany. Journal of Environmental Economics and Management 91, 93-117. https://doi.org/10.1016/j.jeem.2018.06.004.

Tang J.Y., Gu W.Y., Wang M., et al., 2025. Association between extreme temperature events and multimorbidity among older adults: evidence from the CHARLS. BMC Medicine 23(1), 625.https://doi.org/10.1186/s12916.

Guo M., Zheng J., Zhang J., Li J., Wang Q., Lai D.W., 2025. Impact of extreme weather events on mental health among older adults in China: A longitudinal study. Sustainable Cities and Society, 106580.https://doi.org/10.1016/j.scs.2025.106580.

Fang B., Wang Y., 2025. Spatiotemporal heterogeneity of health vulnerability evolution and heatwave impacts among middle-aged and older adults: Based on entropy method and GTWR model. South China Population 40(6), 1-14,78.(In Chinese).

Zhang Q., Li X., Hou Y., et al., 2025. Climate risk and mental health of middle-aged and older adults: Evidence from extreme precipitation. Chinese Journal of Population Science 39(6), 77-92.(In Chinese)

Deng D., Feng Y., 2021. Does community-based elderly care service alleviate health vulnerability among Chinese older adults? Journal of Hubei University (Philosophy and Social Science) 48(5), 150-159, 169. https://doi.org/10.13793/j.cnki.42-1020/c.2021.05.017.(In Chinese)

Goode W.J., 1960. A theory of role strain. American Sociological Review 25(4), 483-496.https://doi.org/10.2307/2092933.

Hughes M.E., Waite L.J., LaPierre T.A., Luo Y., 2007. All in the family: The impact of caring for grandchildren on grandparents' health. The Journals of Gerontology: Series B 62(2), S108-S119.https://doi.org/10.1093/geronb/62.2.S108.

Minkler M., Fuller-Thomson E., Miller D., Driver D., 1997. Depression in grandparents raising grandchildren: Results of a national longitudinal study. Archives of Family Medicine 6(5), 445-452.https://doi.org/10.1001/archfami.6.5.445.

Minkler M., Fuller-Thomson E., 2001. Physical and mental health status of American grandparents providing extensive child care to their grandchildren. Journal of the American Medical Women's Association 56(4), 199-205.https://doi.org/10.1007/s10826-019-01618-y.

Xiao Y., 2017. The impact of intergenerational care on the health status of older adults: An empirical study based on CHARLS. Social Security Studies (1), 33-39.(In Chinese)

Homans G.C., 1961. Social Behavior: Its Elementary Forms. Harcourt, Brace & World, New York.

Blau P.M., 1964. Exchange and Power in Social Life. John Wiley & Sons, New-York.

Ning M., Wang X., 2015. An analysis of the behavioral motivations of intergenerational economic support in Chinese rural families. Journal of Agrotechnical Economics (5), 21-33.https://doi.org/10.13246/j.cnki.jae.2015.05.003.(In Chinese)

Wang H., Wang D., 2025. Heat exposure and self-rated health in older Chinese adults: the mediating roles of chronic disease and intergenerational support, 2008-2018 CLHLS. Frontiers in Public Health 13, 1636724.https://doi.org/10.3389/fpubh.2025.1636724.

Cohen S., Wills T.A., 1985. Stress, social support, and the buffering hypothesis. Psychological Bulletin 98(2), 310-357.https://doi.org/10.1037/0033.

Guo K., Ji Q., Zhang D., 2024. A dataset to measure global climate physical risk. Data in Brief 54, 110502.https://doi.org/10.1016/j.dib.2024.110502.

Ma E., Wang M., 2026. How climate change affects corporate tax behavior. Public Finance Research 47(7), 1347-1376.https://doi.org/10.19477/j.cnki.11-1077/f.2026.07.004.(In Chinese).

Huang F., Cheng Q., 2024. From “universal access” to “equitable access”: An analysis of equity in health security. Finance and Trade Research 35(1),

71-83.https://doi.org/10.19337/j.cnki.34-1093/f.2024.01.006.(In Chinese).

Liu X., Ji L., 2024. How does long-term care insurance affect older adults' mental health? Studies in Labor Economics 12(3), 35-63.(In Chinese).

Zhu M., He M., Ma Z., 2025. The supply-side effect of long-term care insurance from the perspective of spatial agglomeration: Empirical evidence from the elderly-care industry. Management World 41(6), 114-133.https://doi.org/10.19744/j.cnki.11-1235/f.2025.0083.(In Chinese).

Lewbel A., 1997. Constructing Instruments for Regressions with Measurement Error when No Additional Data are Available, with An Application to Patents and R&D. Econometrica 65(5), 1201-1213.https://doi.org/10.2307/2171874.

Qiu Y., Chao Y., Zhang S., 2026. Resource misallocation or cognitive bias: The impact of climate risk on corporate green total factor productivity. Journal of Guangxi Normal University (Philosophy and Social Science Edition) 62(4), 122-137.https://doi.org/10.16088/j.issn.1001-6597.2026.04.012.(In Chinese).

Liu C., Xia J., 2023. Online markets, digital platforms and resource allocation efficiency: The role of price and data mechanisms. China Industrial Economics (7), 84-102.https://doi.org/10.19581/j.cnki.ciejournal.2023.07.004.(In Chinese).

Huang P., Wang C., 2026. The impact of climate warming risk on financial resilience and its countermeasures. Journal of Shenzhen University (Humanities and Social Sciences) 43(4), 70-82.(In Chinese).

Hu Z., Ma S., 2023. The impact of market integration on corporate digital innovation: Also on measurement methods of digital innovation. Economic Research Journal 58(6), 155-172.(In Chinese).

Dong P., 2026. How does artificial intelligence reduce supply chain risk? Evidence based on micro mechanisms and spillover effects. Collected Essays on Finance and Economics 42(5), 28-38.https://doi.org/10.13762/j.cnki.cjlc.2026.05.001.(In Chinese).

Chernozhukov V., Chetverikov D., Demirer M., Duflo E., Hansen C., Newey W., Robins J., 2018. Double/Debiased Machine Learning for Treatment and Structural Parameters. The Econometrics Journal 21(1).https://doi.org/10.1111/ectj.12097.

Kakwani N., 1984. The relative-deprivation curve and its applications. Journal of Business & Economic Statistics 2(4), 384-394.https://doi.org/10.1080/07350015.1984.10509412.

Song C., Zhao Q., Wu L., 2026. The “butterfly effect” of climate change: The

impact and mechanism of heatwaves on the global trade network. China Population, Resources and Environment 36(4), 11-22.(In Chinese).

Zheng D., Huang X., Pan A., 2023. Evaluation and empirical study of economic losses caused by high temperatures in prefecture-level cities from the perspective of labor productivity. Economic Geography 43(6),13-21.https://doi.org/10.15957/j.cnki.jjdl.2023.06.002.(In Chinese).

Miller S., Chua K., Coggins J., et al., 2021. Heat waves, climate change, and economic output. Journal of the European Economic Association 19(5), 2658-2694.https://doi.org/10.1093/jeea/jvab009.

Long X., Wang Z., 2025. From heat to high-tech: How innovation responds to climate change. Journal of Development Economics, 103525. https://doi.org/10.1016/j.jdeveco.2025.103525.