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Association between cold spells and frailty among middle-aged and older adults in China: Evidence from a national longitudinal survey

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Research Article

Keywords: Cold spells, Frailty, CHARLS, Middle-aged and older adults, China

Posted Date: February 24th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-8701131/v1

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Additional Declarations: No competing interests reported.

Abstract

Background

Frailty is a multifaceted clinical syndrome associated with adverse health outcomes. Cold spells, as acute environmental stressors, may expedite the development of frailty. The study aimed to explore the association of cold spells and risk of frailty among older people

Methods

Using data from the China Health and Retirement Longitudinal Study (CHARLS), we conducted a prospective cohort study of 13,578 adults aged ≥ 45 years from 2011 to 2018. Cold spell exposure was assessed using city-level meteorological data and defined by site-specific temperature percentiles (≤ 7.5%, 5%, and 2.5%) and duration (≥ 2, 3, and 4 days). Cox proportional hazard models incorporating time-dependent covariates were utilized to evaluate the impacts of cold spells events on the risk of frailty. Additionally, subgroup analyses were carried out to assess potential modifying effects across various populations.

Results

Across all intensity and duration definitions, each one-unit increase in the natural log-transformed number of cold spell days was associated with a 12.3% (95% CI: 1.089–1.158,) to 14.4% (95% CI: 1.104–1.185) higher risk of frailty after full adjustment. Subgroup analyses revealed stronger associations among older individuals, female, non-drinkers, and those residing in southern regions.

Conclusion

This study provides robust evidence that cold spells contribute to the development of frailty among middle-aged and older adults in China. The effects were more pronounced in specific subpopulations, indicating the need for targeted public health interventions and regionally adapted cold weather preparedness strategies.

Introduction

In the context of the rapid global population aging [1], frailty, defined as a comprehensive health state marked by depleted physiological reserves and decreased stress resistance, has emerged as a notable public health issue [2, 3]. Frailty is typically characterized by a decline in multi-system functions. This makes individuals more susceptible to adverse outcomes when confronted with stress and serves as a vital indicator for evaluating the health and quality of life of the elderly [4]. According to a recent systematic review of 62 countries, pooled prevalence of frailty was 12% when using the physical frailty

assessment and 24% when using the deficit accumulation model globally [5]. In the context of low- and middle-income countries, it was found that the prevalence of frailty and pre-frailty ranged from 3.9% to 59.4% and from 13.4% to 71.6%, respectively [6]. As frailty progresses, it significantly heightens the risk of various adverse health outcomes, including falls, hospitalization, disability, and mortality, which imposes a huge burden on the social medical and care system [7, 8]. Frailty is influenced by both the internal factors of an individual (such as chronic diseases, nutritional status, and lifestyle) and regulated by external environmental factors. It is the product of the interaction between the individual and the environment [9].

In recent years, climate change has resulted in frequent occurrences of extreme weather events. The intensity and duration of extreme cold (cold wave) events have been increasing, posing a threat to individual's health [10]. As an extreme meteorological event characterized by sudden onset, short duration and significant temperature drops, cold spells may affect human health through multiple pathways (precipitate hemodynamic stress, pro-thrombotic shifts, and inflammatory activation), especially among the elderly [11, 12]. Currently, a substantial body of evidence has demonstrated that cold exposure notably elevates the incidence and mortality risk of cardiovascular and cerebrovascular events as well as respiratory diseases among the elderly [13]. Moreover, this risk exhibits a significant upward trend when the temperature falls below a specific threshold.

However, most research primarily focuses on the relationship between extreme temperatures and mortality or a specific type of acute health outcome, with a lack of systematic studies on the relationship between cold spell exposure and the occurrence and progression of frailty, especially among the large scale elderly population in China [14]. Notably, a recent study revealed the correlation between the daily average temperature or the annual average temperature and frailty progression, without involving extreme temperatures event [15].

The China Health and Retirement Longitudinal Study (CHARLS), a nationally representative cohort study targeting middle-aged and elderly individuals aged 45 and above, which has collected extensive information on health, lifestyle, socioeconomic status, and geographical location, offers a rare opportunity to quantify relationships between cold spells and frailty at the national scale [16]. By utilizing this data platform and integrating high-resolution meteorological data with the definition criteria of cold spells, this study intends to systematically evaluate the influence of cold spells on the risk of frailty among the elderly population in China, further investigate potential vulnerable groups and modulating factors, and offer scientific evidence for public health interventions and climate-adaptive policies.

Materials and methods

Data source and study design

A cohort study was conducted using the CHARLS database. The CHARLS database is derived from an ongoing, nationally representative survey. This survey employs a multistage stratified sampling approach

to target Chinese adults aged 45 years and above from 10,000 households, covering 28 province-level, 150 county-level and 450 village-level units. The baseline wave (2011) enrolled 17,708 participants with a response rate of 93.3%. Subsequent follow-up assessments were performed biennially (2013, 2015, 2018, and 2020 waves) [16, 17]. CHARLS provides extensive data on demographic characteristics, socioeconomic status, health behaviors, and biological measurements, with detailed methodological information available in prior publications. Ethical approval for the study was granted by the Peking University Institutional Review Board (IRB No. 00001052–11015), and all participants provided signed informed consent documents.

The flow chart of this study was exhibited in Fig. 1. A total of 17,708 participants were enrolled at baseline, and the exclusion criteria were as follows: (1) absence of age information or age younger than 45 years (N = 648), (2) no frailty information available at the baseline (N = 102), (3) participants diagnosed with frailty at the baseline (N = 2,539), and (4) loss to follow-up or death (N = 841). Ultimately, 13,578 people were included in the present cohort study.

Exposure assessment

Daily mean ambient temperature (°C) at 2 meters for the 125 county-level CHARLS locations from 1973 to 2023 was primarily obtained from the China Meteorological Administration Land Data Assimilation System (CMA-LDAS, version 3.0; https://data.cma.cn/), which integrates observations from 2,420 national meteorological stations. To ensure data completeness, < 1% of missing values were imputed using 5-km resolution ERA5-Land reanalysis data provided by the European Centre for Medium-Range Weather Forecasts. To protect participants' residential privacy, temperature data were linked to individuals at the city level. The number of cold spell days experienced by each participant during the year preceding the follow-up survey was then calculated. This one-year exposure window was employed to capture the time-varying nature of extreme temperature exposure.

According to the previous studies, based on the daily average temperature data of each city in China in a specific year, and adopting a combination of the quantile threshold method and the continuous number of days method, cold spells were defined using site-specific percentiles calculated over the full calendar period: (i) P7.5 (cold spell light), (ii) P5 (cold spell moderate), and (iii) P2.5 (cold spell severe). Simultaneously, for each temperature quantile threshold, low-temperature processes that are continuously ≥ 2 days, ≥ 3 days, ≥ 4 days are identified in sequence (**Table S1**) [18, 19].

Outcome definition

Drawing upon established methodologies in the literature, 32 health deficit indicators were identified from the dataset to construct a frailty index (FI) [20]. These indicators span five domains: functional limitations, self-rated health, components of depressive symptoms, diagnosed disease conditions, and cognitive status. All variables were sourced from participant self-reports combined with objective

assessments. Functional impairments were identified based on reported difficulties in performing activities of daily living (ADLs), instrumental ADLs (IADLs), and other mobility-related limitations. Self-rated health was evaluated through participants' overall health perceptions. Components of depressive symptoms were derived from the 10-item Center for Epidemiologic Studies Depression Scale (CESD-10), which asks participants whether they experienced specific emotional states during the past week, with binary (yes/no) response options. Chronic disease diagnoses were obtained from self-reports of physician-confirmed conditions, with each survey wave including a validation step to confirm previous reports. Cognitive status was evaluated using a combination of self-reported diagnoses and cognitive performance scores. Comprehensive details for all variables are provided in **Table S2**. To optimize sample size, we implemented several approaches: individuals with more than 10% missing data for any variable were excluded, remaining missing values were handled via multiple imputation, and the FI was calculated as the arithmetic mean of all health deficit variables multiplied by 100, yielding a final range from 0 to 100. Consistent with prior studies, frailty was defined as an FI score of 25 or higher [21].

Covariates

Potential confounders selected a priori included: age (years, continuous); gender (male vs female); marital status (yes/no); residence (rural vs urban); education (below primary, primary school, middle school, high school, or college and above); region (south vs north); sleep duration (< 6 hours vs ≥ 6 hours); current drinking (yes/no); current smoking (yes/no); body mass index (BMI) category (< 18.5, 18.5–24.9, 25.0–29.9, ≥ 30); physical activity (MET-hours/week: <600, 600–2999, ≥ 3000); socioeconomic status (poor, fair, good); heating fuels (clean fuels [e.g., electricity, gas] vs solid fuels [e.g., coal, wood]); and cooking fuels (clean fuels [e.g., electricity, gas] vs solid fuels [e.g., coal, wood]). All the above information was obtained at baseline using a structured questionnaire.

Statistical analysis

To address right-skewed distributions and the presence of zero values in certain variables, natural logarithmic transformation of the form ln (x + 1) was applied prior to analysis [22]. This approach helps improve the normality of the data and stabilizes variance across observations. The description of variables and their transformations were shown in **Table S3**. The distribution of cold spells was characterized by a high frequency of zero values and a small number of positive values, resulting in a markedly right-skewed pattern. This zero-inflated and skewed nature of the data necessitated appropriate transformation prior to analysis (**Table S4**).

The demographic and clinical characteristics of the study participants were presented through descriptive statistics. Continuous variables were expressed as means ± standard deviations, and categorical variables were reported as frequencies (%). Comparative analyses were carried out between the groups with and without frailty using appropriate statistical tests: the Pearson's Chi-squared test was applied for categorical variables, and the Wilcoxon rank - sum test was used for continuous variables.

Next, in order to assess the relationship between cold spells and frailty, Cox proportional hazards regression models were utilized to calculate hazard ratios (HRs) along with their corresponding 95% confidence intervals (CIs). The weighted Schoenfeld residuals test was utilized to evaluate the proportional hazards assumption [23]. Survival time was computed in years, starting from the baseline interview and concluding at either the first documented diagnosis of frailty or the final interview in 2018, whichever took place earlier. According to the previous studies [15], four models were adopted in this study: Model 1 was unadjusted; Model 2 was adjusted for demographic factors (age, gender, marry, residence, education, and region); Model 3 additionally incorporated lifestyle factors (sleep duration, smoking, and drinking); Model 4 was further adjusted for heating fuels and cooking fuels. Stratified and interaction analyses were subsequently carried out to evaluate whether the association between cold spells and frailty differed including age (< 60 vs ≥ 60 years), gender, marital status, residence, region, sleep duration, drinking status, smoking status, and heating fuels. Each stratum was examined within an adjusted model. To assess effect modification, multiplicative interaction terms of cold spells and relevant covariates were included in the model. All analyses were conducted in R (version 4.5.0). Statistical significance was set at a two-sided $p < 0.05$.

Sensitivity analyses

To evaluate the robustness of the results, sensitivity analyses were conducted, which included mitigating the influence of missing data in the CHARLS dataset and the effect of variable transformation. The MissForest algorithm was utilized in our study to impute the missing values within the dataset (**Table S5**). The MissForest is a non-parametric, iterative imputation method based on random forests. It handles both continuous and categorical variables without assuming underlying distributions. By leveraging patterns in observed data, it uses an ensemble of decision trees to predict missing values. In our analysis, we set the number of trees (ntree) to 100 to improve imputation stability and accuracy [24]. Secondly, we compare the values of the regression model before and after the transformation of variables.

Results

Population characteristics

Table 1 presents the baseline characteristics of 13,578 participants included in the analysis. The mean age of the study population was 58.11 ± 9.07 years. Overall, males and females were almost equally represented (50.2% vs. 49.8%). Among all participants, 3,522 individuals were classified as frail. Compared with non-frail participants, those with frailty were older and more likely to be female, unmarried, and living in rural areas. Frail participants also tended to have lower educational attainment and shorter sleep duration. In terms of lifestyle and health-related factors, frailty was associated with a higher prevalence of low or obese body mass index, lower levels of physical activity, and poorer socioeconomic status. Additionally, the use of solid fuels for both heating and cooking was more common among frail individuals. The frailty index was substantially higher in the frail group than in the

non-frail group, supporting the validity of the frailty classification. The geographical distribution of all participants as well as those with frailty was presented in **Figure S1**.

Table 1
Population characteristics of the participants at baseline

Characteristic	All participants (*N* = 13,578)	Non-Frailty (*N* = 10,056)	Frailty (*N* = 3,522)	p-value[1]
Age, Mean ± SD	58.11 ± 9.07	56.89 ± 8.51	61.62 ± 9.68	< 0.001
Gender, n (%)				< 0.001
Female	6,757 (49.8%)	4,591 (45.7%)	2,166 (61.5%)	
Male	6,821 (50.2%)	5,465 (54.3%)	1,356 (38.5%)	
Marital status, n (%)				< 0.001
Unmarried	1,426 (10.5%)	862 (8.6%)	564 (16.0%)	
Married	12,150 (89.5%)	9,192 (91.4%)	2,958 (84.0%)	
Residence, n (%)				< 0.001
Urban	5,428 (40.0%)	4,274 (42.5%)	1,154 (32.8%)	
Rural	8,150 (60.0%)	5,782 (57.5%)	2,368 (67.2%)	
Education, n (%)				< 0.001
Below primary school	6,041 (44.5%)	3,884 (38.6%)	2,157 (61.2%)	
Primary school	2,880 (21.2%)	2,201 (21.9%)	679 (19.3%)	
Middle school	2,879 (21.2%)	2,407 (23.9%)	472 (13.4%)	
High school	1,778 (13.1%)	1,564 (15.6%)	214 (6.1%)	
Region, n (%)				0.019
South	7,527 (55.4%)	5,634 (56.0%)	1,893 (53.7%)	
North	6,051 (44.6%)	4,422 (44.0%)	1,629 (46.3%)	
Sleep duration, n (%)				< 0.001
< 6 hours	3,286 (26.2%)	2,132 (23.1%)	1,154 (34.9%)	
≥ 6 hours	9,245 (73.8%)	7,089 (76.9%)	2,156 (65.1%)	
Drinking status, n (%)				< 0.001
No	8,757 (64.6%)	6,175 (61.5%)	2,582 (73.5%)	
Yes	4,790 (35.4%)	3,858 (38.5%)	932 (26.5%)	
Smoking status, n (%)				< 0.001
No	9,033 (69.2%)	6,460 (67.1%)	2,573 (74.8%)	

Characteristic	All participants (*N* = 13,578)	Non-Frailty (*N* = 10,056)	Frailty (*N* = 3,522)	p-value[1]
Yes	4,029 (30.8%)	3,163 (32.9%)	866 (25.2%)	
BMI categories, n (%)				< 0.001
Low-body weight	678 (6.3%)	422 (5.3%)	256 (8.8%)	
Normal body weight	4,581 (42.4%)	3,460 (43.7%)	1,121 (38.6%)	
Overweight	2,256 (20.9%)	1,723 (21.8%)	533 (18.3%)	
Obesity	3,301 (30.5%)	2,306 (29.1%)	995 (34.3%)	
Physical activity, n (%)				< 0.001
Low	815 (15.4%)	560 (14.5%)	255 (18.1%)	
Moderated	1,012 (19.2%)	722 (18.7%)	290 (20.6%)	
High	3,449 (65.4%)	2,585 (66.8%)	864 (61.3%)	
Socioeconomic status, n (%)				< 0.001
Poor	2,018 (21.0%)	1,288 (18.4%)	730 (27.8%)	
Fair	4,712 (49.0%)	3,359 (48.0%)	1,353 (51.4%)	
Good	2,893 (30.1%)	2,346 (33.5%)	547 (20.8%)	
Heating fuels, n (%)				< 0.001
Clean	3,994 (36.0%)	3,276 (40.0%)	718 (24.7%)	
Solid	7,103 (64.0%)	4,916 (60.0%)	2,187 (75.3%)	
Cooking fuels, n (%)				< 0.001
Clean	6,378 (47.6%)	5,091 (51.3%)	1,287 (37.1%)	
Solid	7,014 (52.4%)	4,828 (48.7%)	2,186 (62.9%)	
FI, Mean ± SD	9.47 ± 6.45	7.87 ± 5.72	14.05 ± 6.20	< 0.001

[1] Continuous data were presented as the median ± standard error with Pearson's Chi - squared test employed for group comparison. Categorical data were presented as frequency (and percentage) with the Wilcoxon rank - sum test utilized for group comparison.

BMI, body mass index; FI, frailty index.

Exposure to cold spell events

Table S4 summarizes the distribution of cold spell exposure across different definitions and survey waves. During the first follow-up wave, the average number of cold spell days per elderly individuals

ranged from 6.71 to 20.83 days. In 2014 and 2017, the average numbers of cold spell days were 6.92–19.20 and 7.13–19.83, respectively. To account for right-skewed distributions, natural-log transformations of cold spell days (i.e., ln (days + 1)) were also calculated.

Association between cold spells and risk of frailty

After natural-log transformation, significant positive associations were observed between cold spell exposure and the development of frailty across all exposure definitions (Fig. 2, **Table S6**). In the unadjusted model (Model 1), each one-unit increase in the natural log-transformed number of cold spell days was associated with a 6.0% to 7.8% higher risk of frailty (e.g., HR for CS1 (P7.5_2d): 1.060, 95% CI: 1.041–1.079; HR for CS9 (P2.5_4d): 1.078, 95% CI: 1.051–1.106). After adjusting for demographic and socioeconomic factors (Model 2), the hazard ratios increased, ranging from 1.117 to 1.133. These associations remained stable after further controlling for lifestyle factors such as BMI, sleep duration, and smoking and drinking status (Model 3), with HRs between 1.139 (CS5 (P5_3d)) and 1.162 (CS9 (P2.5_4d)). Even after full adjustment in Model 4, which additionally accounted for heating and cooking fuel types, the effect estimates persisted, with HRs ranging from 1.123 (CS5 (P5_3d), 95% CI: 1.089–1.158) to 1.144 (CS9 (P2.5_4d), 95% CI: 1.104–1.185), all statistically significant ($p < 0.05$). These consistent findings across varying definitions and models suggest that prolonged exposure to cold spells may be an independent environmental risk factor for frailty among older adults.

Notably, in the crude model, the risk of frailty generally increased with the increase in intensity and duration of cold spells, ranging from 1.060 (1.041, 1.079) in CS1 (P7.5_2d) to 1.078 (1.051, 1.106) in CS9 (P2.5_4d) after natural-log transformation. After adjusting the models, elderly individuals exposed to moderate cold spells had a lower risk of frailty (e.g., Model 4, HR for CS6 (P5_4d): 1.127, 95% CI: 1.093–1.163). By contrast, elderly individuals exposing in light or severe cold spells were more likely to suffer from frailty. Among them, the highest hazard ratio was 1.146 (1.107, 1.186) in CS2 (P7.5_3d).

Subgroup analyses

Subgroup analyses revealed that factors such as age, gender, geographic region, and alcohol consumption significantly influenced the risk of frailty in older adults, while marry status, residence, smoking consumption, sleep duration, and heating fuels showed no significant association (Fig. 3, **Table S7, S8, S9, S10, S11, S12, S13, S14, S15**). Specifically, individuals of an older age demonstrated a greater susceptibility to severe cold spells (CS (P2.5)), as indicated by hazard ratios ranging from 1.202 to 1.213 after natural-log transformation. Furthermore, elderly individuals residing in southern regions were found to be more vulnerable to the effects of cold spells, with hazard ratios of 2.746 (95%CI: 1.693–4.455). In comparison to males, females were found to be more vulnerable to the effects of cold spells presented a significantly elevated risk associated with cold spell events, showing a 15.7% increase in risk (HR: 1.157, 95% CI: 1.107–1.209) for each one-unit increase in the natural log-transformed number of cold spell days. Notably, when compared with drinkers, non-drinkers suffered a higher risk of frailty during the light cold spell (P7.5), with HRs of 1.149, 1.152, and 1.143 during periods of ≥ 2 days, ≥ 3 days, and ≥ 4 days respectively.

Sensitivity analyses

After addressing missing data through the MissForest method, we conducted Cox proportional hazards regression analyses again. The results demonstrated strong and consistent statistically significant positive relationships between exposure to cold spells and the risk of frailty (**Table S16**). Additionally, in order to verify the results before and after the natural logarithmic transformation of the data, COX regression analyses were conducted again. Finally, the results were robust (**Table S17**).

Discussion

This representative national cohort study confirmed a significant association between cold spells and frailty in the elderly over 45 years old in China. It also demonstrated that this association is more pronounced among the elderly, females, non-drinkers, and individuals living in southern regions. This finding is consistent with existing research on the health impacts of extremely low temperatures and further reveals, from a new perspective, the influence of environmental exposure on the physiological homeostasis and frailty process in the elderly.

Frailty is a clinical syndrome characterized by a state of reduced physiological reserves in the body, impaired functions of multiple systems, and heightened susceptibility to external stresses such as diseases and environmental stimuli [3, 25]. This indicates that individuals are at a higher likelihood of experiencing health deterioration or functional decline when encountering short-term or mild stress (such as infection, low temperature, high temperature) compared to healthy individuals. Generally, frailty is defined with five domains, including functional limitations, self-rated health, components of depressive symptoms, diagnosed disease conditions, and cognitive status [20]. At present, most of the researches focused on studying the association between frailty-related indicators and extreme temperature events. For example, Sun et al. focused on how extreme temperature events affect the risk of stroke. Among these events, cold spells had a positive effect on stroke, with a hazard ratio of 1.149 (1.062, 1.243) [26]. Furthermore, other researchers paid attention on comorbidity, such as cardiometabolic multimorbidity or general multimorbidity, which has also demonstrated a positive association between cold spells and the risk of disease conditions [13, 27]. Previous findings from Chinese Longitudinal Healthy Longevity Survey (CLHLS) demonstrated that individuals with impaired physical functional status exhibited significantly higher vulnerability (HR 2.23–3.74) of cold spells-related mortality [28]. Additionally, regarding depression and cognitive function, previous studies verified that extreme temperature events affect the progression of these conditions [29, 30]. Given that the majority of the aforementioned studies have focused on the relationship between extreme temperature events and individual frailty indicators (e.g., functional limitations, depression, cognition, and disease), there is still a lack of empirical evidence for systematic research that integrates these dimensions into a comprehensive frailty index. Recently, a study related to average temperature and frailty progression have been published [15]. However, our study expanded upon this line of inquiry by integrating cold spells into the analysis. This enabled us to highlight the unique and heightened impact of extreme climatic stressors on frailty dynamics, which meaningfully expands current research in aging and public health.

The impact of cold spells on human health is a complex process involving multiple physiological pathways, including the interaction among the vascular, metabolic and immune systems. In cold environments, the activity of the sympathetic nervous system increases, causing strong peripheral vasoconstriction, which in turn raises blood pressure and heart rate, and increases the burden on the cardiovascular system [31, 32]. Moreover, cold-induced sympathetic activation can lead to an unstable heart rate, an increase in myocardial oxygen consumption, and a hypercoagulable state of the blood [11]. Additionally, among the elderly population, arterial compliance is diminished, and they already have underlying problems such as atherosclerosis and vascular endothelial dysfunction. The drastic changes in blood vessels induced by cold can easily trigger acute cardiovascular and cerebrovascular events, including myocardial infarction and stroke [33]. To the best of our knowledge, when exposed to cold, the body activates non shivering thermogenesis largely mediated by brown adipose tissue (BAT). While the acute activation of BAT enhances energy expenditure and promotes thermal homeostasis, prolonged or recurrent cold stress may redirect systemic energy allocation towards thermogenesis, potentially restricting the energy available for other physiological processes. Furthermore, the activation of BAT modifies whole-body substrate metabolism, including alterations in circulating free fatty acids and glucose utilization, suggesting that cold-induced thermogenic responses can exert more extensive impacts on metabolic homeostasis [34–36]. A meta-analysis revealed that during cold wave, diabetes-related mortality risk increased by 40% (relative risk (RR): 1.40, 95% CI: 1.25–1.58), and morbidity risk elevated slightly (RR: 1.27, 95CI%: 0.99–1.63) [37]. There exists a complex interaction between exposure to cold spells and the immune system, particularly among the elderly, and this interaction may facilitate the development of frailty. Firstly, low temperature can impact the function of immune cells and their energy allocation, consequently affecting the body's response to infection and inflammation [38]. Subsequently, cold exposure regulated inflammation via immune system. Previous study found that cold exposure leads to the inhibition of immune response-related pathways in ferret aPVAT (aortic perivascular adipose tissue), which aggravates the inflammation of blood vessels and results in the development of atherosclerosis [39]. Furthermore, exposure to cold conditions reduces the expression of MHCII on monocytes both under baseline conditions and across multiple inflammatory mouse models, thereby impairing T cell priming via monocyte-mediated regulatory mechanisms [40]. Some studies additionally discovered that low-temperature conditions are capable of regulating immune responses via neurotransmitter pathways (e.g., norepinephrine), and intricately modifying cytokine expression and the distribution of white blood cells [41]. In conclusion, the synergistic effect of these three factors (vascular, metabolic, and immune systems) renders the elderly more susceptible to functional decline, physical deterioration, exacerbation of chronic diseases, and progression of frailty syndrome in cold environments.

The stratification analysis results revealed that individuals who were older, female, consumed alcohol, and resided in the southern region were more sensitive to cold spells. Initially, compared to younger individuals, the elderly exhibit markedly heightened sensitivity to low-temperature environments. This increased vulnerability is closely associated with age-related declines in thermoregulatory capacity, a higher prevalence of comorbid conditions, and the growing burden of chronic diseases [32, 42].

Furthermore, our study found that females demonstrated a higher level of vulnerability to cold spells. Research has demonstrated that women have a higher mortality risk than men in extreme temperatures, particularly in cold weather [43, 44]. This might be associated with women's physiological sensitivity to temperature changes (e.g., hormonal or immune regulation) and their vulnerability in terms of socioeconomic status (e.g., outdoor exposure, lifestyle) [45]. Although our results indicated that non-drinkers were confronted a higher risk of frailty during the light cold spell compared with drinkers, this association may reflect epidemiological phenomena such as the healthy drinker effect or confounding by quitters [46, 47], rather than a protective effect of drinking itself. Therefore, it should be interpreted with prudence and should not serve as a basis for health recommendations that advocate drinking. Finally, individuals residing in southern regions exhibited greater sensitivity to cold spells. Research indicated that inhabitants of southern regions possess weaker adaptability to extreme cold weather due to their limited exposure to such conditions in daily life. Consequently, they encounter higher health risks during cold spells [43, 48]. Moreover, the infrastructure and public health systems (e.g., heating equipment) in southern regions might not be as well-developed as those in the north, which can further intensify the health impacts of cold spells [49].

The results of this study suggest that public health strategies should place greater emphasis on the impact of cold spells on the frailty process of the elderly. To this end, a multi-pronged approach is recommended. Firstly, an integrated prevention framework should be developed, linking cold spells early-warning systems with routine frailty screening for the elderly. This would facilitate the timely identification of at-risk individuals and allow for preemptive support. Secondly, infrastructure and policy measures must be enhanced, including the improvement of community heating facilities and the implementation of energy subsidy programs. These steps are crucial to mitigate the direct adverse effects of low temperatures on the daily functioning of older populations. Thirdly, comprehensive interventions aimed at bolstering resilience should be promoted. Such measures include tailored physical activity programs for functional maintenance and nutritional support strategies, both designed to improve the capacity of older adults to cope with cold-related physiological stress.

While this study leverages nationally representative longitudinal data from the CHARLS cohort to investigate the association between cold spells exposure and frailty in older adults, several limitations need to be noted. Firstly, the assessment of cold exposure was conducted at the city or county scale, potentially failing to accurately represent individual-level thermal conditions, including indoor environments or housing quality. Secondly, the measurement of frailty relied on self-reported indicators in the absence of objective physical performance assessments, a methodology that could introduce reporting bias. In addition, the dataset lacks detailed information on behavioral responses to cold exposure, such as heating use or changes in daily activity, which could influence vulnerability. Finally, given the observational nature of the study, the possibility of residual confounding factors cannot be entirely ruled out, and causal inferences should therefore be drawn cautiously.

Conclusion

This study, based on the CHARLS database, demonstrates that cold spells are associated with an increased risk of frailty among middle-aged and older adults. More pronounced effects are observed in older individuals, women, and residents of southern regions. These findings underscore the need for region-specific and population - sensitive strategies to protect vulnerable groups from cold-related health risks.

Declarations

Acknowledgements

We sincerely express our gratitude to the China Health and Retirement Longitudinal Study (CHARLS) team for granting us access to the data and for their substantial contributions to its collection, curation, and management.

Authors' contributions

Xinji Li: Writing-original draft, Visualization, Validation, Methodology, Software, Formal analysis, Data curation. **Jinming Lin**: Writing-original draft, Visualization, Validation, Methodology, Software, Formal analysis, Data curation. **Xian Yang**: Writing-original draft, Methodology, Investigation, Formal analysis, Validation. **Hui Zhang**: Writing-review & editing, Conceptualization, Project administration, Investigation, Funding acquisition. **Gaowei Guo**: Writing-review & editing, Conceptualization, Project administration, Investigation. All authors consent to publication.

Funding

This study was supported by Guangdong Medical Research Foundation (A2024395).

Data availability

The data utilized in this study are sourced from the China Health and Retirement Longitudinal Study (CHARLS), which is hosted by the National School of Development, Peking University. The datasets are publicly accessible to registered researchers who fulfill an online data - use agreement through the official CHARLS portal ((http://charls.pku.edu.cn). All analytical code and materials necessary for reproducing the findings can be obtained from the corresponding author upon reasonable request.

Ethics approval and consent to participate

CHARLS obtained ethical clearance from the Institutional Review Board of Peking University (IRB00001052-11015). All participants provided written informed consent, and subsequently, the data were de-identified to guarantee confidentiality. The current analyses were performed on this anonymized, publicly accessible dataset. No additional ethics review was necessary for secondary use. The study protocol was examined and approved by the Institutional Review Board of Xinxiang Medical University (XYLL - 2019072) and was implemented in line with the principles of the Declaration of Helsinki.

Competing interests

The authors declare no competing interests

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Figures

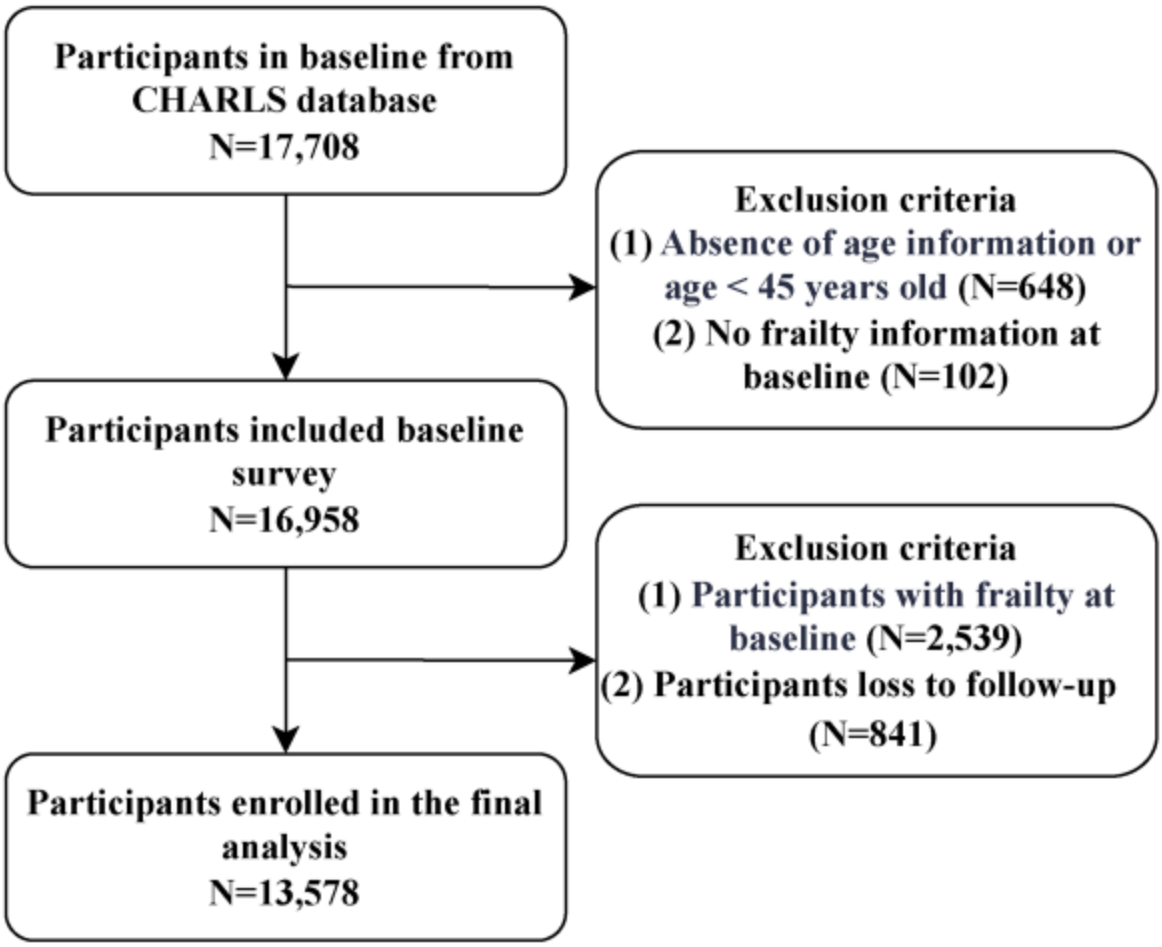


Figure 1

Flow chart of selection criteria

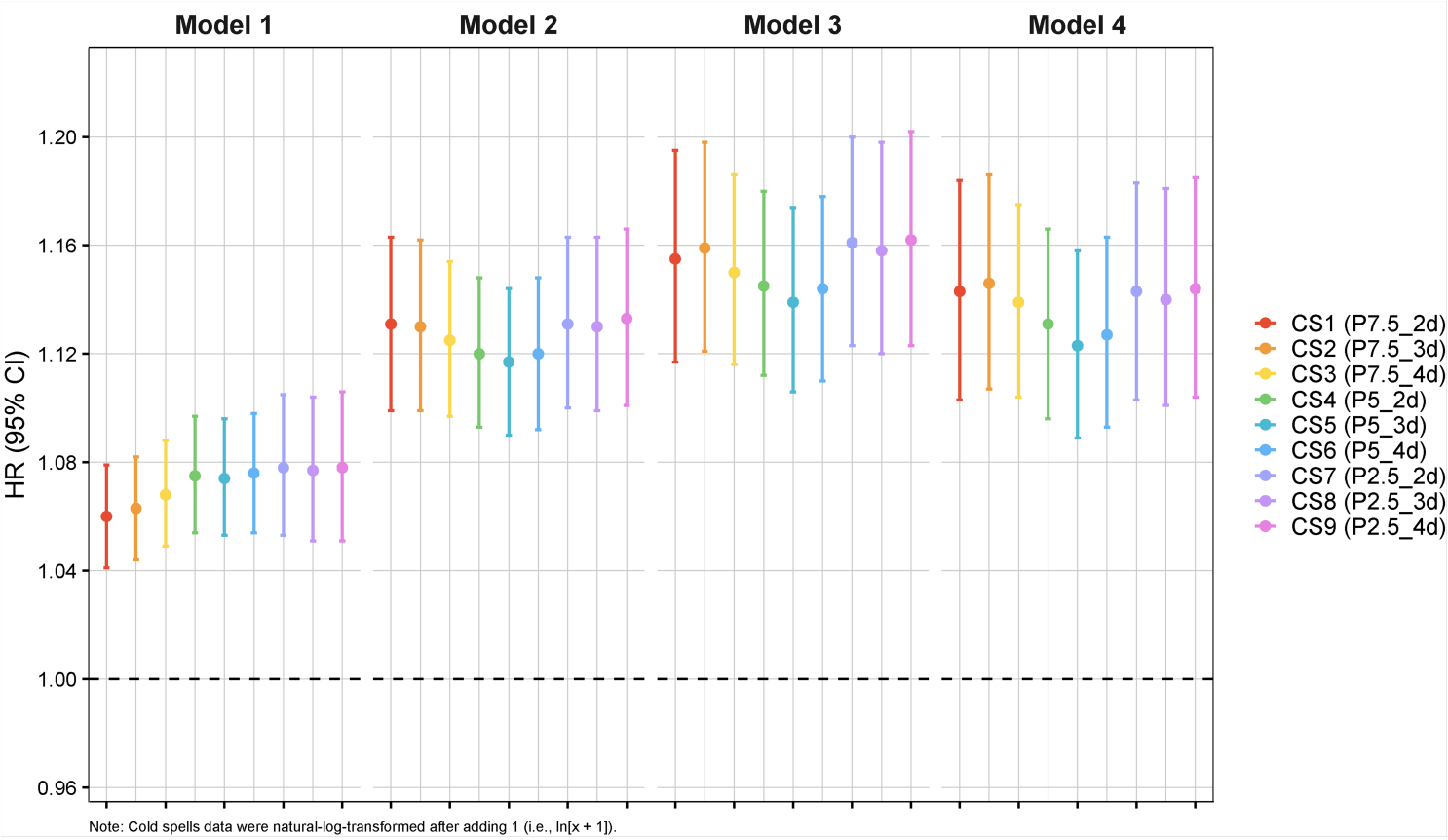


Figure 2

Association between cold spells and the risk of frailty. Abbreviations: CS, cold spell; HR, hazard ratio; CI, confidence interval. Model 1, unadjusted. Model 2, adjusted for age, gender, marry, residence, education and region. Model 3, adjusted for age, gender, marry, residence, education, region, BMI categories, sleep duration, drinking status, smoking status. Model 4, adjusted for age, gender, marry, residence, education, region, BMI categories, sleep duration, drinking status, smoking status, heating fuels and cooking fuels

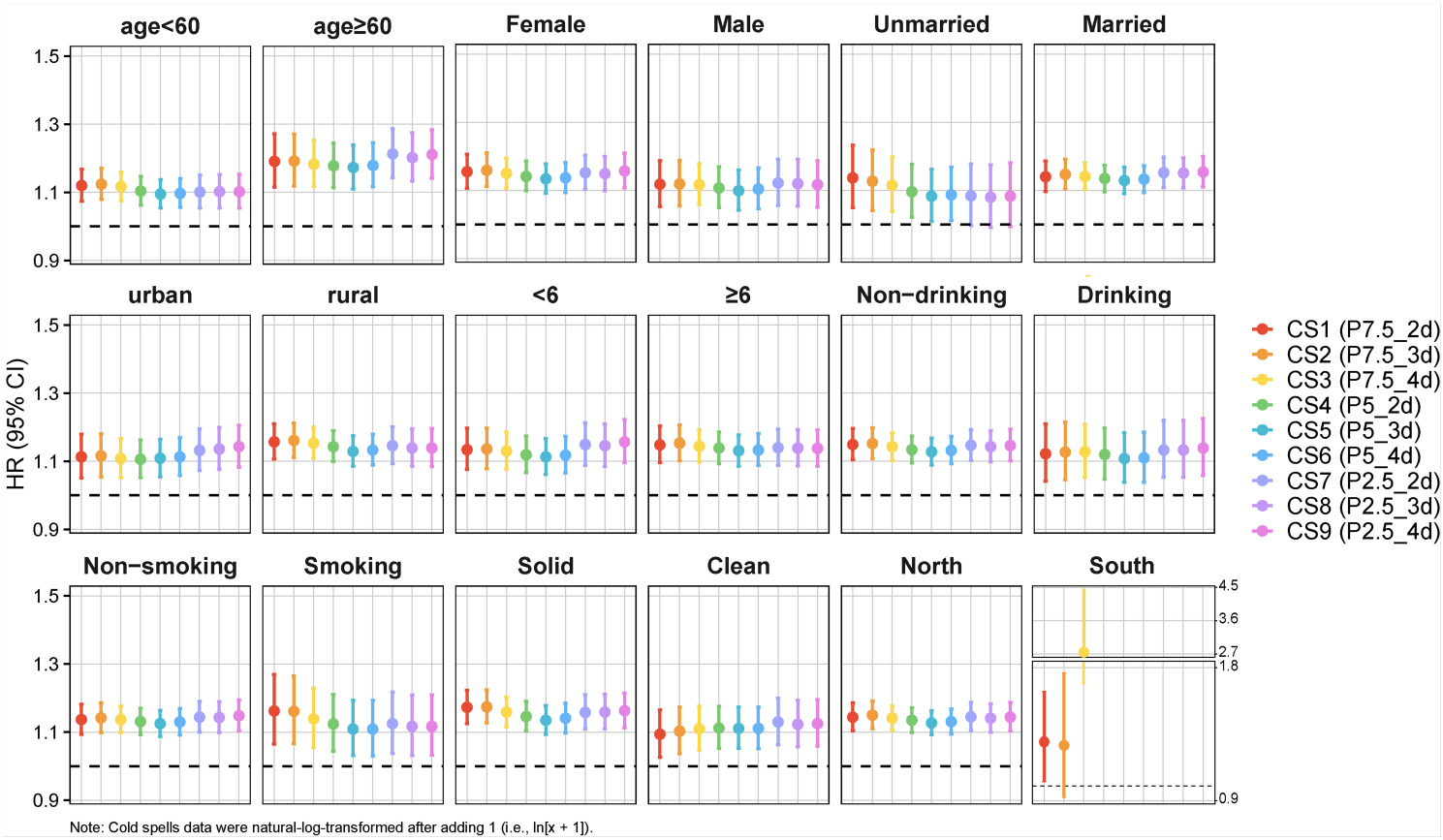


Figure 3

Subgroup analyses of association of cold spells with frailty by age, gender, marry status, residence, sleep duration, drinking status, smoking status, heating fuels, and region. Abbreviations: CS, cold spell; HR, hazard ratio; CI, confidence interval. The Cox proportional hazard models were adjusted for age, gender, marry, residence, education, region, BMI categories, sleep duration, drinking status, smoking status, heating fuels and cooking fuels

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