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Cumulative Intersection Risks of Aging and Climate Vulnerability: A Spatiotemporal Analysis Based on Global Public Databases

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ABSTRACT

Global population aging and climate change are creating mutually reinforcing, intersecting cumulative risks, yet their nonlinear amplification mechanisms have not been systematically quantified. This study integrates open data sources, including the World Bank World Development Indicators (WDI), Lancet Countdown, NASA Goddard Institute for Space Studies (GISS), and the International Disaster Database (EM-DAT). Taking 30 sample countries from 1990 to 2023 as research subjects, it constructs the Intersecting Cumulative Risk Index (ICRI) and conducts spatiotemporal overlay analysis on the rates of population aging and temperature anomalies. The heat-related mortality data adopted in this research are derived from model estimations of the Global Burden of Disease (GBD), rather than raw statistics from national vital registration systems; all analyses are performed based on such modeled data, and relevant inferences should be interpreted within this epistemological framework. The study's findings are as follows: (1) The proportion of the global population aged 65 and above keeps rising, with East Asian economies such as China and Japan experiencing far faster aging than high-income countries in comparable historical periods; (2) Heat-related mortality rises nonlinearly. Globally, heat deaths among people aged 65 and older in 2023 increased by approximately 167% compared with the 1990s. If only demographic shifts are considered (under the assumption of constant climatic conditions), around 65 percentage points of the growth can be attributed to population aging. The remaining excess growth of roughly 102 percentage points is provisionally estimated as the net effect of climate change superimposed on population aging—this decomposition is derived from the Lancet Countdown's modelled counterfactuals and should be interpreted as a structural breakdown rather than an independently identified causal attribution—this net effect covers both direct physiological impacts of rising temperatures and the intersecting cumulative amplification of aging and warming; (3) Countries with low Human Development Index (HDI) scores feature relatively mild population aging yet severe adaptation deficits. Disparities in air conditioning penetration lead to a 19-fold gap in the ratio of air conditioning-preventable deaths, generating institutional intersecting vulnerability; (4) Dimensions including gender, urban-rural divides, and living arrangements further amplify heterogeneous risks among elderly populations. This research suggests that population aging and climate vulnerability are not merely additive but may be mutually reinforced through three pathways: physiological-climatic coupling, socio-spatial accumulation, and economic-institutional accumulation. It provides empirical evidence for incorporating an elderly justice perspective into climate adaptation policies.

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1. Introduction

The 21st century witnesses two structural transformations confronting human societies: unprecedented global population ageing and accelerated deviation of the Earth's climate system from pre-industrial equilibrium. The UN World Population Prospects 2024 projects that the share of people aged 65 and above worldwide will reach 16% by 2050, with this demographic transition advancing at divergent speeds across East Asia, South Asia, and sub-Saharan Africa [1]. Meanwhile, observational data from NASA GISS indicate that the global average surface temperature has increased by roughly 1.1°C relative to the 1880–1900 baseline, with warming rates further accelerating during 2010–2023 [2].

Traditionally, population ageing and climate change have been treated as separate policy domains. Mounting evidence, however, points to profound intersectionality between the two phenomena: older adults exhibit markedly higher vulnerability to climate extremes than other age groups, due to depleted physiological reserves, multimorbidity, fractured social networks, and insufficient economic resources [3]. The UNEP Frontiers 2025 Report estimates that annual heat-attributable deaths among the elderly have climbed by 85% since the 1990s [4]. The Lancet Countdown 2024 Report further documents a 54% rise in heat-driven mortality among older populations over the past two decades [5].

Nevertheless, existing research generally treats ageing and climate risks as isolated variables or only adopts simple linear superposition, overlooking nonlinear amplification effects arising from their interaction. This study develops the conceptual framework of Intersecting Cumulative Risks, stressing that compound impacts of demographic ageing and climate change reinforce each other via physiological, social, and institutional pathways to generate systematically escalating vulnerabilities over time. Drawing on global open-access datasets, this cross-national analysis quantifies such intersecting cumulative risks and identifies core risk-amplifying mechanisms and priority intervention areas.

A critical methodological clarification is warranted: the core heat-related mortality indicator (Indicator 1.1.5) from the Lancet Countdown relied upon in this paper is not raw mortality statistics directly reported by national vital registration systems, but modelled estimates developed under the GBD framework [5]. Official methodological documentation of the Lancet Countdown clarifies that this metric is estimated via composite models combining temperature-mortality exposure-response functions, population structures, baseline mortality rates, and temperature distributions. Accordingly, this paper constitutes a secondary analysis of global public modelled datasets, occupying an epistemological position between primary empirical research and pure simulation work. All analyses are executed on these modelled outputs, and all derived inferences must be contextualised within this analytical framework.

2. Literature Review and Theoretical Framework

2.1. Intersectionality of Ageing and Climate Vulnerability

Coined by Crenshaw (1989) from critical race theory and feminist legal studies, intersectionality theory was initially applied to analyse compound discrimination based on race and gender [6]. This paper borrows its core analytical logic—that combined disadvantages stemming from multiple identities or conditions may exceed the sum of every single dimension—to interpret interactions between old age and climate risks. We do not claim that older adults experience identical structurally marginalised identities as those framed in racial-gender justice scholarship, nor do we equate age-based vulnerability with systems of racial or patriarchal oppression. Ageing is a near-universal biological process rather than a socially constructed category of exclusion (though its social consequences are socially mediated), and its intersection with climate risk operates primarily through physiological degradation and institutional resource deprivation rather than through historical systems of domination. Therefore, the application herein is strictly limited to the formal analytical utility of intersectionality—namely, that compound stressors (demographic ageing and climatic warming) may generate synergistic harms that resist additive decomposition—without invoking the normative or ontological commitments of critical race and feminist theory.

This analytical lens has been increasingly incorporated into climate and health research in recent years. Ebi et al. [7] argue that climate vulnerability in older populations originates not merely from biological senescence, but is cross-sectionally shaped by poverty, gender, residential segregation, and limited healthcare access. In Asia, Neelam Singh et al. [8] find that older women face dual disadvantages during heatwave alerts due to heavy unpaid care responsibilities and limited financial autonomy. A systematic review by Zhongguo Huang et al. [9] covering European settings confirms larger mortality surges among elderly women during heatwaves, with solitary living further widening this disparity.

2.2. Cumulative Risk Theory

Cumulative risk theory (Evans & Schamberg, 2009) posits that sequential exposure to adverse stressors yields health harms exceeding the sum of individual adverse events [10]. Translated to climate-health research, this framework implies recurrent low-intensity heat exposure may inflict irreversible cardiovascular damage on older adults, while discrete extreme events (heatwaves, floods) can trigger cascading failures by disrupting medical supply chains and dismantling social support networks. A global multicentre time-series study by Gasparrini et al. [11] verifies J-shaped or U-shaped temperature-mortality relationships, with far steeper curves for older populations, indicating their physiological buffering capacities are already close to critical thresholds.

2.3. Theoretical Framework: Three Mechanisms of Intersecting Cumulative Risks

Synthesising the above literature, this study establishes the following analytical framework:

Mechanism 1: Physiological-Climate Coupling

Older adults feature reduced bodily water content, blunted thirst perception, and impaired sweat gland function, weakening thermoregulatory capacity. Meanwhile, commonly prescribed medications, including diuretics, antipsychotics, and beta-blockers, disrupt thermal homeostasis and electrolyte balance, preventing the minimum mortality temperature threshold of elderly populations from shifting upward in tandem with anthropogenic warming, a phenomenon described in the geriatric literature as a "physiological lock-in effect" [3].

Mechanism 2: Social-Spatial Accumulation

Older adults are disproportionately concentrated in single-storey housing or urban heat islands, with limited capacity for vertical evacuation during floods and scarce green space to mitigate heat stress. Widowed, solitary individuals or those with shrunken social circles lack diverse channels to receive heatwave early warnings. Survey data indicate 17.5% of participating older adults reported they would not contact anyone for assistance during heatwaves.

Mechanism 3: Economic-Institutional Accumulation

Low-income older persons cannot afford sustained cooling expenses or post-disaster reconstruction and relocation costs. Older residents in long-term care facilities fully depend on electricity-powered life-support systems; extreme weather-driven infrastructure outages trigger exponentially escalated risks. While countries with low HDI exhibit milder population ageing, scarce adaptive resources create severe adaptation deficits.

3. Data and Methods

3.1. Data Sources

This study integrates the following publicly available databases:

Database	Core Indicators	Time Coverage	Geographic Scope
World Bank World Development Indicators (WDI)	Share of population aged 65+ (SP.POP.65UP.TO.ZS), old-age dependency ratio (SP.POP.DPND.OL)	1990–2023	30 sample countries
Lancet Countdown	Indicator 1.1.5 (heat-related mortality), heat threat days, air conditioning accessibility	1990–2024	Global/national
NASA GISS / Berkeley Earth	Annual temperature anomalies, heatwave frequency	1880–2025	Global/national
EM-DAT International Disaster Database	Frequency of extreme weather events, affected populations, and economic losses	1990–2023	Global

Sample countries are selected to ensure representativeness, covering very high-HDI economies (the United States, Japan, Germany, the United Kingdom, France, etc.), high-HDI economies (China, Brazil, Mexico, Thailand, etc.), medium-HDI economies (Indonesia, Vietnam, Philippines, India, etc.), and low-HDI economies (Nigeria, Pakistan, Bangladesh, etc.), totalling 30 nations.

3.2. Construction of the Intersecting Cumulative Risk Index (ICRI)

To quantify compound intersecting risks from ageing and climate hazards, we develop the ICRI as a conceptual framework:

$$ICRI_{i,t} = \alpha \cdot \Delta P_{i,t} + \beta \cdot \Delta T_{i,t} + \gamma \cdot (\Delta P_{i,t} \times \Delta T_{i,t})$$

Where $\Delta P_{i,t}$ denotes the rate of change in the share of population aged 65 and above for country i in year t; $\Delta T_{i,t}$ represents the concurrent rate of temperature anomaly change; the interaction term γ captures potential intersecting cumulative effects. It is important to note that the ICRI serves as an analytical heuristic rather than an independently estimable index; its coefficients are interpreted through the lens of the regression model in Section 3.3. In the empirical estimation, $\Delta P_{i,t}$ and $\Delta T_{i,t}$ are mean-centered to ensure that the interaction term reflects the marginal amplification effect at average rates of change, rather than a mechanical by-product of both variables being positive. A statistically significant positive γ is consistent with risk amplification between population ageing and climate warming, though it does not, by itself, establish the underlying causal mechanism. The coefficients α, β, and γ are estimated through the two-way fixed-effects panel regression model specified in Section 3.3, where γ corresponds to the interaction term coefficient β_3 in the regression equation.

3.3. Regression Model Specification

A two-way fixed-effects panel regression model is adopted to control time-invariant national heterogeneity (e.g., geographic location, institutional legacies) and universal time-varying global shocks (e.g., pandemics, technological transformations). The model is specified as:

$$\ln(M_{i,t}) = \beta_0 + \beta_1 P_{i,t} + \beta_2 T_{i,t} + \beta_3 (P_{i,t} \times T_{i,t}) + \beta_4 X_{i,t} + \mu_i + \lambda_t + \epsilon_{i,t}$$

Where: $M_{i,t}$ = heat-related mortality among populations aged ≥65 in country i, year t (log-transformed to mitigate heteroskedasticity); $P_{i,t}$ = proportion of population aged 65 and above; $T_{i,t}$ = annual temperature anomaly relative to the 1951–1980 reference period; $P_{i,t} \times T_{i,t}$ = ageing-temperature interaction term; $X_{i,t}$ = vector of confounding covariates including log GDP per capita, healthcare expenditure as a share of GDP, urbanisation rate, HDI and annual average PM2.5 concentrations; μ_i = country fixed effects; λ_t = year fixed effects; $\epsilon_{i,t}$ = error term.

Given the limited sample of 30 countries, parallel fixed-effects (FE) and random-effects (RE) estimations are implemented to avoid excessive loss of degrees of freedom under FE models, with Hausman tests deployed for model selection. Standard errors are clustered at the national level to accommodate serial correlation within countries across years. The full dataset comprises 30 countries × 34 years = 1020 observations; incomplete Lancet Countdown data reduce the effective analytical sample to approximately 876 observations. Multiple imputation (m=5) is applied to handle missing values.

3.4. Attributional Decomposition Method

The decomposition of total growth in elderly heat-related mortality into demographic and climatic components employs a counterfactual approach built upon the Lancet Countdown's modelled outputs. The Lancet Countdown's Indicator 1.1.5 is estimated via composite models combining temperature-mortality exposure-response functions, population structures, baseline mortality rates, and temperature distributions, and inherently embeds climate attribution logic through counterfactual comparisons (scenarios with and without anthropogenic climate change) [5].

To isolate the pure demographic contribution (approximately 65 percentage points), we apply the 1990s age-specific mortality and population structure to later-period temperature distributions under the assumption of constant climatic conditions, following the demographic standardisation method. The difference between this counterfactual and the observed baseline yields the ageing-only effect. The residual (approximately 102 percentage points) represents the net superimposed effect of climate change, which encompasses both direct physiological impacts of rising temperatures and the intersecting cumulative amplification generated by the interaction between demographic ageing and climatic warming. It should be emphasised that this decomposition constitutes a structural breakdown of modelled outputs rather than an independent identification of discrete causal mechanisms. The counterfactual assumption of static climatic conditions is structurally embedded in the Lancet Countdown's modelled outputs but cannot be independently verified against observed data. All derived inferences should therefore be treated as exploratory and descriptive rather than causally identified.

4. Empirical Results

4.1. Model Diagnostics

Prior to presenting the main empirical results, we report diagnostic tests for the regression model specified in Section 3.3. Variance Inflation Factor (VIF) tests yield VIF values below 3.5 for all explanatory variables, ruling out severe multicollinearity. The Wooldridge test detects no significant within-group first-order serial correlation. The Modified Wald test confirms cross-group heteroskedasticity, which is addressed via cluster-robust standard errors.

Model selection between fixed-effects (FE) and random-effects (RE) specifications was guided by the Hausman test, which yielded a chi-squared statistic of 23.4 (p = 0.003), rejecting the null hypothesis of no systematic difference between FE and RE estimators. We therefore report FE estimates as the primary specification, with RE estimates presented for sensitivity comparison in the table.

Variable	FE (Primary)	RE (Sensitivity)
Proportion aged 65+ ($P_{i,t}$)	0.045***	0.038***
	(0.012)	(0.011)
Temperature anomaly ($T_{i,t}$)	0.032**	0.028*
	(0.014)	(0.015)
Ageing × Temperature ($P_{i,t} \times T_{i,t}$)	0.018***	0.012**
	(0.006)	(0.005)
log(GDP per capita)	–0.125	–0.098
	(0.089)	(0.076)
Healthcare expenditure (% of GDP)	0.008	0.012
	(0.015)	(0.013)
Urbanisation rate	0.003	0.005
	(0.004)	(0.004)
HDI	0.256	0.198
	(0.198)	(0.176)
Annual average PM2.5	0.002*	0.001
	(0.001)	(0.001)
Constant	2.456	2.189
	(0.567)	(0.489)
Country fixed effects	Yes	No
Year fixed effects	Yes	Yes
Clustered standard errors	Yes	Yes
Observations	876	876
R^2 (within / overall)	0.72	0.68
Hausman test		
χ^2 (8)	23.40	
p-value	0.003	

Notes: Standard errors clustered at the country level are reported in parentheses. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

4.2. Accelerating Global Population Ageing

Analysis of World Bank WDI data reveals universal accelerated ageing across sample countries with striking regional disparities:

- United States: The share of residents aged 65+ rose from 12.3% in 1990 to 17.4% in 2023, with the old-age dependency ratio climbing from 19.0% to 26.8%, representing an average annual growth of 0.15 percentage points.
- Japan: As a super-aged society, Japan maintains the world's highest proportion of people aged 65+ throughout the sample period, reaching 29.9% in 2023 with an old-age dependency ratio exceeding 50%.
- China: The share of population aged 65+ surged from roughly 5.6% in 1990 to 14.9% in 2023, with an average annual growth rate of 0.28 percentage points, far outpacing concurrent trends in high-income nations.
- India, Nigeria: Current proportions of adults aged 65+ remain below 7%, yet their absolute elderly populations are substantial (104 million in India, 11 million in Nigeria), with projected rapid growth in the coming decades.

WDI-derived results demonstrate compressed ageing across East Asian economies (China, Japan, South Korea), completing demographic transitions that unfolded over decades in Western nations within a compressed timeframe, imposing acute pressure on social security and healthcare systems.

4.3. Intersecting Cumulative Effects on Heat-Related Mortality

Indicator 1.1.5 from the Lancet Countdown provides the most comprehensive global longitudinal tracking of elderly heat mortality [5]. Analytical outcomes are summarised below:

(1) Nonlinear Temporal Cumulation

- Baseline (1990s): Annual global heat-attributable deaths among adults aged ≥65 averaged 335,000 cases (based on the mean of annual estimates from Lancet Countdown Indicator 1.1.5 for 1990–2000).
- 2012–2021 average: Rose to 546,000 cases, a 63.2% increase.
- 2023: Record-breaking growth, marking a 167% rise relative to the 1990s baseline (calculated as the percentage change from the 1990–2000 mean to the 2023 point estimate of Lancet Countdown Indicator 1.1.5).

Crucially, this growth cannot be decomposed into simple additive contributions from ageing and climate warming alone. If only demographic shifts are considered (under the assumption of constant climatic conditions), approximately 65 percentage points of the growth can be attributed to population ageing. The remaining excess growth of roughly 102 percentage points is provisionally estimated as the net effect of climate change superimposed on population aging—this net effect covers both direct physiological impacts of rising temperatures and the intersecting cumulative amplification of aging and warming. That is, the 102-percentage-point residual already embeds the interaction between demographic ageing and climatic warming, because the physiological vulnerability of an ageing population amplifies the health impacts of temperature increases. This decomposition is derived from the Lancet Countdown's modelled counterfactuals and should be interpreted as a structural breakdown rather than an independently identified causal attribution. A critical caveat: the Lancet Countdown dataset inherently embeds climate attribution models via counterfactual comparisons (scenarios with and without anthropogenic climate change). The decomposition presented herein constitutes a structural breakdown of modelled outputs rather than an independent identification of discrete causal mechanisms. Estimation of the ICRI interaction term relies on extrapolation of temperature-mortality exposure-response functions provided by the Lancet Countdown, instead of independently collected mortality panel data.

(2) Exposure-Vulnerability Matrix

A stratified matrix constructed using 2024/2025 Lancet Countdown data highlights the central role of adaptation deficits:

HDI Group	Additional heat threat days in 2023 (vs. no-climate-change counterfactual)	Growth in heat-related mortality (≥65), 1990s–2023	Household air conditioning penetration	Air conditioning-driven preventable death ratio
Very High HDI	Limited (yet high absolute burden)	+139%	48.4%	0.76
High HDI	Moderate	+228%	43.8%	0.74
Medium HDI	Substantial	+194%	14.3%	0.12
Low HDI	Severe	+240%	4.7%	0.04

The air conditioning-driven preventable death ratio is defined as the estimated share of heat deaths that would be avoidable under a counterfactual scenario in which household air conditioning penetration in each HDI group is scaled to the mean level observed in very high-HDI economies (48.4%), holding all other factors constant. This calculation is derived from the Lancet Countdown's exposure-response functions and should be interpreted as a hypothetical lower-bound estimate of unidimensional adaptive capacity, not as a causally identified treatment effect.

Notably, the ratio reaches only 0.76 in very high-HDI economies, implying that even universal air conditioning access at current penetration levels would leave approximately 24% of heat deaths unabated. This ceiling effect reflects inherent limitations of air conditioning as a standalone intervention: it cannot protect older adults during outdoor exposure, power grid failures, or extreme wet-bulb temperature events exceeding mechanical cooling capacity. Consequently, the 0.04 ratio in low-HDI nations represents a lower-bound estimate; multi-dimensional interventions (building retrofits, early warning systems, urban greening) would likely yield higher preventable proportions, though their joint effects cannot be quantified with available public data. At merely 0.04 for low-HDI nations, this metric indicates 96% of heat deaths cannot be averted through air conditioning access alone. This disparity does not stem from higher ageing prevalence (low-HDI countries feature smaller elderly population shares), but institutional intersecting vulnerability: insufficient adaptive resources and weak infrastructure expose older adults to disproportionate hazards under identical temperature anomalies. It must be emphasised that air conditioning penetration functions only as a single proxy for adaptive capacity; behavioural adaptation, institutional emergency responses, healthcare accessibility, and community support networks exert equally vital impacts. Combined effects of multi-dimensional adaptive interventions would likely yield higher preventable mortality ratios, yet constrained public data availability prevents comprehensive quantification of joint adaptive effects, leaving this avenue open for future research.

4.4. Granular Empirical Evidence from Europe

The *Lancet Countdown Europe 2026 Report* delivers higher-resolution regional evidence [12]:

- 99.6% of European monitoring stations recorded elevated heat-related mortality between 2015–2024 relative to the 1991–2000 baseline, with an average annual increase of 52 heat deaths per million residents.
- Cumulative heatwave exposure person-days for infants (<1) and older adults (≥65) surged by 254%, rising from 460 million to 1.63 billion person-days.
- Record-breaking summer temperatures in 2024 generated 2.3 billion heatwave person-days exclusively borne by Europe's elderly populations.

European case studies particularly illustrate dose-response relationships for cumulative heat exposure: repeated low-intensity thermal stress inflicts long-term physiological damage to older adults' bodily systems, manifesting in elevated all-cause mortality in subsequent years rather than only acute heat stroke fatalities within the same heatwave period.

4.5. Intersecting Dimensions of Compound Inequity

Older adults form a heterogeneous population. Cross-analysis of multi-source datasets identifies stratified subpopulation risks:

- **Gender**: Older women experience higher poverty rates and twice the likelihood of post-traumatic stress disorder following climate disasters compared to men. Women also bear disproportionate unpaid caregiving responsibilities under climate stress, squeezing time dedicated to personal health maintenance.
- **Urban-Rural Residence**: Urban older adults face heat island effects, associated with a 2.24-fold increase in mortality risk; rural elderly populations suffer limited healthcare access, evacuation barriers and delayed warning information dissemination. Urban-rural disparities are most pronounced in rapidly urbanising medium-HDI nations.
- **Living Arrangements**: Elderly residents of long-term care facilities exhibit significantly higher heatwave mortality than community-dwelling seniors. Institutional standardised protocols fail to accommodate individualised thermal regulation needs (e.g., impaired temperature perception among dementia patients), and care facilities fully rely on external power grids and supply chains.
- **HDI Stratification**: Low-HDI countries record the steepest growth in elderly heat mortality (+240%), yet suffer the most severe data gaps. EM-DAT records reveal systematic underreporting of extreme weather events across these regions, overlapping surveillance blind spots with adaptive resource shortages.

5. Discussion

5.1. Mechanistic Interpretation

Empirical results from this study provide empirical support for the three pathways of intersecting cumulative risk theory:

The physiological-climate coupling mechanism is supported by nonlinear temperature-mortality relationships. NASA GISS records document a 1.1°C global average temperature anomaly rise, with high-latitude nations (Russia, Canada) experiencing warming of 2.5–3°C. The thermoregulatory systems of older adults cannot rapidly adjust to such rapid shifts, widening the gap between minimum mortality temperature thresholds and ambient temperatures. Regularly administered medications (diuretics, antipsychotics, anticholinergics) further erode adaptive capacity, creating what geriatric researchers describe as a "physiological lock-in effect".

The social-spatial accumulation mechanism is reflected in stratified risks across living arrangements and urban-rural divides. Cross-referenced World Bank and EM-DAT data demonstrate that older adults residing in low-lying single-storey housing sustain higher property losses and mortality during floods. Spatial overlap between urban heat islands and elderly residential zones (ageing neighbourhoods with limited green space) creates what urban geographers term "risk traps" —persistent exposure hotspots that are difficult to escape without structural intervention.

Economic-Institutional Accumulation Mechanism is most salient in cross-national adaptation deficit metrics. Air conditioning penetration stands at merely 4.7% in low-HDI nations versus 48.4% in very high-HDI economies. This gap reflects not only income disparities but also integrated institutional capacities spanning electrical infrastructure, building standards, and social safety nets. Concurrent extreme weather disruptions to power and transportation networks trigger healthcare system surges, interrupting routine elderly care, including dialysis, chronic disease medication access, and rehabilitation services, leading to cascading systemic failures.

5.2. Dialogue with Existing Literature

The intersecting cumulative risk amplification identified herein aligns with the global multicentre findings of Gasparrini et al. [11], yet further delineates the moderating role of population ageing dynamics. Gasparrini et al. documented regional heterogeneity in temperature-mortality curves without systematically examining cross-national disparities in ageing speeds; this paper incorporates demographic transition rates and identifies statistically significant positive ageing-warming interaction terms, filling a critical gap in existing scholarship.

Furthermore, our quantification of adaptation deficits aligns with Lancet Countdown Indicator 2.3 (Adaptation and Resilience) [5], yet operationalises adaptive capacity measurement via the novel elderly-specific air conditioning-driven preventable death ratio, introducing an actionable metric for climate justice research.

5.3. Study Limitations

This research is constrained by structural limitations inherent to open-access global datasets:

- **Incomplete national temperature-mortality panel records**: While Berkeley Earth and NASA GISS deliver high-quality temperature anomaly data, Lancet Countdown estimates for Global South nations rely heavily on modelled imputation due to absent primary vital registration data, particularly lacking continuous time-series coverage across sub-Saharan Africa and South Asia. This restricts the generalisation of the ICRI index to low-income regions.
- **Scarce compound disaster datasets**: EM-DAT archives discrete single-hazard events but lacks systematic tracking of elderly-specific harms under compound concurrent crises (heatwaves + power outages, floods + infectious disease outbreaks). Case studies, including the 2021 Texas winter storm and 2022 Pakistan floods, indicate elderly fatalities from compound hazards are dispersed across disjoint statistical categories.
- **Insufficient granularity for social determinant data**: World Bank WDI supplies national-level ageing proportions but lacks subnational spatial overlays mapping elderly population distribution and heat exposure at neighbourhood or municipal scales. Microdata capturing social networks, caregiving arrangements, and housing quality remain absent from mainstream open-access databases.
- **Challenges for causal identification**: This study adopts descriptive and exploratory analytical approaches and cannot fully account for time-varying national confounding variables. The fixed-effects specification cannot rule out time-varying confounders that evolve gradually within countries, such as medical technological advances (which may systematically underestimate heat deaths if incompletely incorporated into Lancet Countdown models), ground-level ozone surges during heatwaves (generating co-exposure confounding), or sequential public health reforms. The decomposition of 167% growth into 65 percentage points (ageing) and 102 percentage points (climate residual) relies on the counterfactual assumption of static climatic conditions, which is structurally embedded in the Lancet Countdown's modelled outputs but cannot be independently verified against observed data. All derived inferences should therefore be treated as exploratory and descriptive rather than causally identified. Future research may deploy instrumental variable designs or difference-in-differences frameworks leveraging discrete policy shocks (e.g., national heatwave early warning rollouts) to strengthen causal inference.

6. Conclusions and Policy Recommendations

6.1. Core Conclusions

Cross-sectional integrated analysis of global open-access datasets suggests that intersecting cumulative risks of population ageing and climate vulnerability may constitute a quantifiable global health crisis. Principal conclusions are summarised as follows:

- The interaction between global population ageing and anthropogenic warming is associated with nonlinear growth in heat-related mortality. Approximately one-third of total growth in heat deaths among adults aged ≥65 between 1990~2023 cannot be explained by isolated single factors and requires the intersecting cumulative interaction effect for full interpretation.
- Intersecting cumulative risks propagate via three mutually reinforcing pathways: physiological-climate coupling, social-spatial accumulation, and economic-institutional accumulation, generating substantial stratification across HDI tiers, gender, urban-rural residence, and living arrangements.
- Low-HDI nations face dual blind spots: overlapping data gaps for both demographic ageing and climate health impacts, compounded by extreme scarcity of adaptive resources, rendering these regions the most marginalised priority within global climate justice agendas.

6.2. Policy Recommendations

The following policy interventions are derived from the empirical findings of this study where directly supported by the data, and from the broader literature reviewed in Section 2, where the study's open-access datasets lack the necessary granularity.

(1) Integrated Data Infrastructure and Surveillance Systems

Establish a unified open-access data platform integrating ageing, climate, and health metrics, consolidating WDI, Lancet Countdown, GHCN-Daily, and national vital registration systems. Prioritise strengthening cause-of-death surveillance and real-time temperature-mortality linkage monitoring in Global South nations to close critical surveillance blind spots.

(2) Centring Older Persons' Justice in Climate Adaptation

Classify older adults as priority vulnerable populations within National Adaptation Plans (NAPs) and disaster risk management frameworks, avoiding one-size-fits-all policies that overlook marginalised elderly subgroups. Integrate an elderly vulnerability weighting mechanism into adaptation funding allocation, directing disproportionate financial support toward nations experiencing rapid demographic ageing paired with severe adaptation deficits.

(3) Sustainable Cooling and Retrofitted Housing Policies

Scale passive cooling architectural design (shading, natural ventilation, green roofs, high-albedo building materials), subsidise air conditioning units and electricity bills for low-income older households. Prioritise green and blue infrastructure expansion surrounding elderly residential zones in urban planning to mitigate urban heat island intensity.

(4) Resilient Healthcare and Long-Term Care Systems

Integrate climate-related health hazards into geriatric and nursing professional training, equipping clinical staff to recognise atypical heat illness presentations (e.g., absent profuse sweating in elderly heat exhaustion patients). Based on evidence from existing geriatric and nursing literature rather than direct empirical analysis of pharmaceutical data in this study, revise pharmaceutical regimens for older adults during heatwave alerts, suspending or adjusting medications impairing thermoregulation. Mandate backup independent power supplies (UPS/generators) and a minimum 72-hour reserve of pharmaceuticals, food, and potable water for all long-term care facilities.

(5) Community Early Warnings and Social Support Networks

Implement formal buddy check systems pairing isolated elderly residents with community volunteers for in-person heatwave alert outreach. Deploy low-technology non-digital warning communication channels (community radio broadcasts) to bridge digital divide barriers. Support elderly participatory climate action groups to strengthen social cohesion and individual climate resilience.

Data Availability Statement

All datasets utilised in this study are publicly accessible open resources. World Bank WDI data can be retrieved via https://data.worldbank.org; Lancet Countdown data via https://www.lancetcountdown.org; NASA GISTEMP temperature data via https://data.giss.nasa.gov/gistemp; Berkeley Earth datasets via https://berkeleyearth.org; EM-DAT disaster records via https://www.emdat.be. Full calculation code for the ICRI index and complete analytical scripts are available upon request to the corresponding author.

CRediT authorship contribution statement

Liam Holt: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Chloe Dubois:** Writing – original draft. **Miguel Torres:** Writing – review & editing. **Aisha Nwosu:** Writing – review & editing. **Hanna Olsen:** Writing – review & editing, Methodology, Conceptualization.

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