Climate Change and an Aging Society:

The Rapid Increase of Heatstroke Deaths in Japan (1972-2022)

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Introduction

The impact of climate change on human health, such as the increasing risk of heatstroke, is becoming a growing concern globally (IPCC 2022). This is particularly critical in aging societies, as older individuals are more vulnerable to extreme heat. While previous studies have highlighted the link between rising temperatures and increased mortality (e.g., Luthi et al. 2023, Zhang et al. 2023), there has been limited spatio-temporal research specifically analyzing the number of deaths directly caused by heatstroke. This gap exists due to data constraints, making it difficult to accurately assess the direct impact of heatstroke. Japan offers long-term, individual-level detailed heatstroke mortality data. This study applied a hierarchical Bayesian spatio-temporal model to investigate how summer temperature anomalies and elderly population proportions have influenced municipal-level heatstroke deaths (n=1,831 municipalities) across Japan.

To understand the long-term patterns of heatstroke mortality in Japan, we first conducted an overview analysis of annual heatstroke deaths from 1972 to 2022, covering both the ICD-9 and ICD-10 coding periods. Given the change in classification systems, the spatio-temporal modeling and risk factor analysis were restricted to the period from 1995 onward, when the ICD-10 coding system was consistently applied.

Data and Methods

We used individual-level heatstroke death records from 1972 to 2022, sourced from Japan's vital statistics. These records include information on age, gender, and place of residence for each decedent. Heatstroke deaths are identified using the International Classification of Diseases (ICD) system, with: ICD-9 Code 992 used for deaths from 1972–1994 to capture deaths related to heat and light, and ICD-10 Code T67 used for 1995–2022 for deaths related to heatstroke and heat exhaustion.

For this study, these individual-level data were aggregated to the municipal level (n=1,831 municipalities) for analysis. Linear regression was performed on heatstroke death trends for each municipality, with significance tested across the data. Additionally, the average heatstroke deaths per 100,000 people for each municipality over the study period were calculated. For the spatio-temporal modeling, we compiled a panel dataset covering monthly heatstroke deaths counts for 1,831 municipalities across Japan from 1995 to 2022.

The explanatory variables included:

- Standardized summer temperature anomalies (June, July, August), calculated relative to the 1980–1994 baseline period, using data from the Japan Meteorological Agency's AMeDAS observation network.
- Proportion of elderly population (aged 65 years and older) in each municipality, derived from the population census.

To examine the spatial and temporal variability in heatstroke mortality, we implemented a series of hierarchical Bayesian Poisson regression models using the Integrated Nested Laplace Approximation (INLA) framework.
Specifically, we developed the following three models:

1. Spatial model: Incorporating spatially structured and unstructured random effects at the municipal level.
2. Spatio-temporal model: Extending the spatial model by adding temporal random effects to capture year-to-year variation.
3. Spatio-temporal interaction model: Further including a space-time interaction term to account for localized deviations from overall spatial and temporal trends.

Model performance was evaluated using the Deviance Information Criterion (DIC) and the Watanabe-Akaike Information Criterion (WAIC) to identify the best-fitting model.

Results

Over the study period, heatstroke deaths in Japan increased dramatically, rising from 42 deaths in 1972 to 1,617 in 2022 (Figure 1). When adjusted for population, the rate of heatstroke deaths per 1 million people increased from 0.39 to 12.94. When comparing deaths using the ICD-10 code T67 over the period from 1995 to 2022, heatstroke deaths rose from 337 in 1995 to 1,617 in 2022.

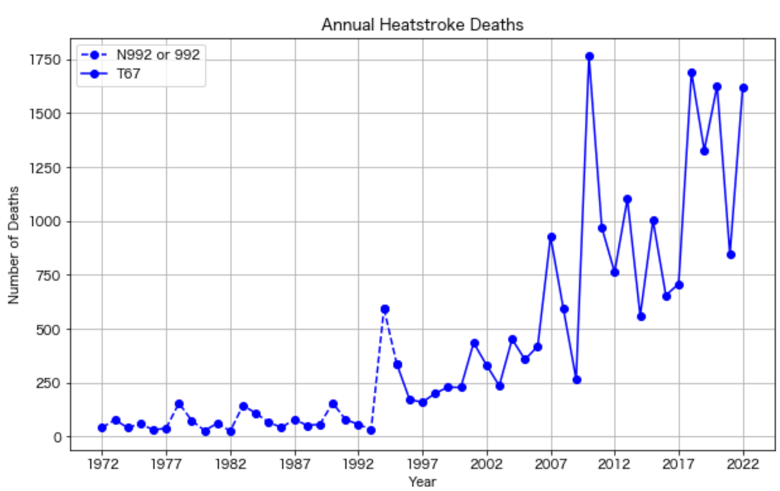

Figure 1. Change in annual heatstroke deaths in Japan 1972-2022: The data from 1972 to 1994 are based on mortality records classified under ICD-9 using code N922 (or 922), while the data from 1995 to 2022 are based on ICD-10 code T67, following the introduction of the ICD-10 in 1995.

Spatial distribution of heatstroke mortality showed that high mortality spread across Japan (Figure 2). Most municipalities with significant trends (except one) showed positive increases (n=372) during 1995–2022. These trends have been observed in urban areas (e.g., Tokyo, Osaka) as well as in rural areas.

(a) (b)

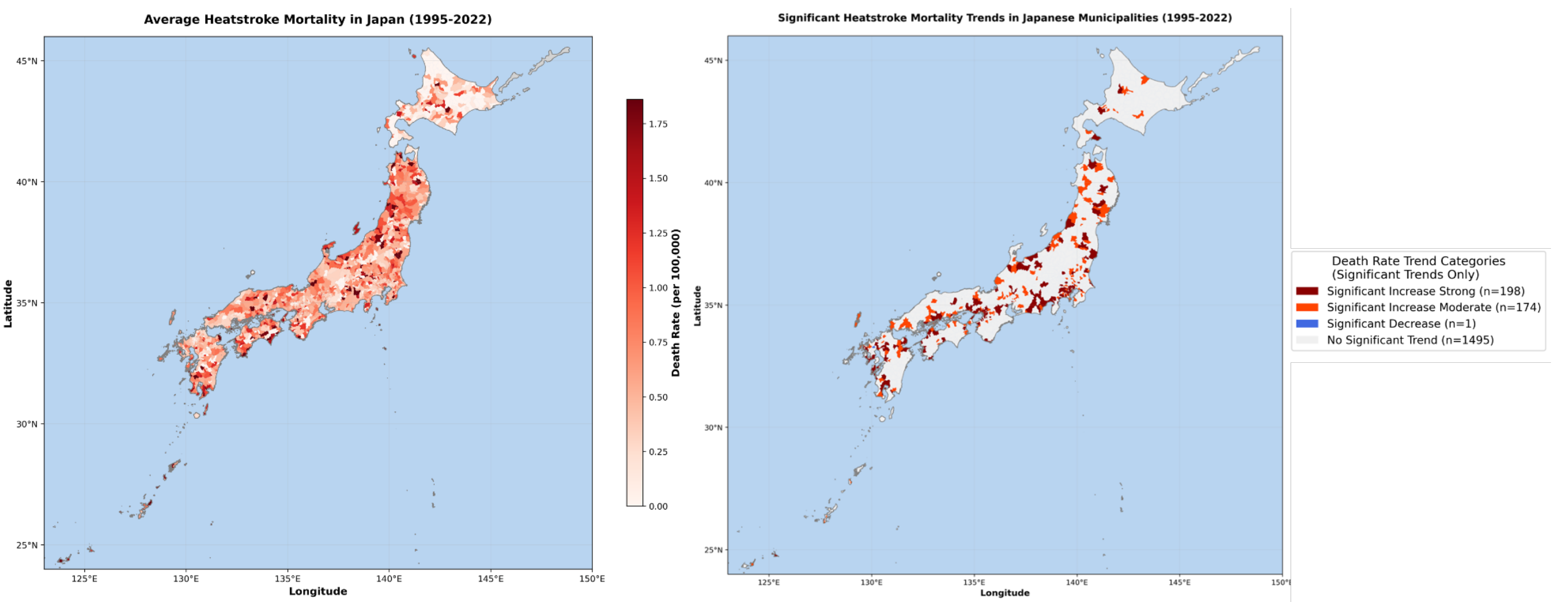

Figure 2. Spatial distribution of heatstroke mortality by municipalities during 1995-2022. (a) Average heatstroke death per 100,000 (b)Trend of heatstroke mortality. Dark red indicates strong significant increase ($p < 0.01$, positive slope), orange indicates moderate significant increase ($0.01 \leq p < 0.05$, positive slope), blue indicates significant decrease ($p < 0.05$, negative slope), and light gray represents areas with no statistically significant trend ($p \geq 0.05$).

The results from our hierarchical Bayesian spatio-temporal modeling are summarized in Table 1. Model comparison based on DIC and WAIC indicated that the spatio-temporal interaction model (Model 3) provided the best fit among the three models tested. Both the summer temperature anomaly and elderly population ratio coefficients showed positive associations with heatstroke mortality, with 95% credible intervals that did not include zero. The estimated coefficient for the standardized summer temperature anomaly was 0.35 (95% CrI: 0.31–0.40), indicating that a one-unit increase (equivalent to +0.647°C above the baseline mean) was associated with a 42% increase in heatstroke mortality. For the elderly population ratio, the coefficient was 2.14 (95% CrI: 1.60–2.68), meaning that each 1 % increase in the rate of elderly was associated with a 2.2% increase in heatstroke mortality.

	Model 1 Spatial model	Model 2 Spatio-temporal model	Model 3 Spatio-temporal interaction model
Temperature anomaly	0.53 [0.51-0.56]	0.34 [0.30-0.38]	0.35 [0.31-0.40]
Elderly ratio	7.43 [7.15-7.71]	1.39 [0.85-1.92]	2.14 [1.60-2.68]
DIC	61775	58889	58099
WAIC	62003	59055	58156

Discussion

Japan's experience highlights the dual challenges of climate change and population aging, offering insights for other countries facing similar demographic transitions.The longitudinal heatstroke mortality data enabled robust analysis of both long-term national trends and municipality-level risk factors. Overall, the number of heatstroke deaths increased rapidly, from 42 in 1972 to 1,617 in 2022. By comparison, heatstroke deaths in the U.S. increased from 1,069 in 1999 to 2,325 in 2023 (Howard et al. 2024), while Japan saw an increase from 229 deaths in 1999 to 1,617 in 2022 (Figure 1). These figures show that while both countries are experiencing rising mortality from heatstroke, Japan's increase has been particularly dramatic. Furthermore, the increasing trend in heatstroke mortality was statistically significant, demonstrating that this is a nationwide issue affecting both urban and rural regions (Figure2).

Our hierarchical Bayesian analysis demonstrated that the spatio-temporal interaction model provided the best fit (Table1), indicating that accounting for localized space-time variations is crucial for accurate risk assessment. This result highlights that heatstroke mortality exhibits complex spatial heterogeneity that varies over time, requiring sophisticated analytical frameworks beyond simple temporal or spatial models alone. The interaction model showed two distinct but synergistic risk mechanisms: climate factors showing 42% mortality increase per standardized temperature unit (approximately +0.65°C), and demographic factors demonstrating 2.2% increase per percentage point of elderly population.

These quantified relationships underscore the need for effective policy responses to address the increasing risk of heatstroke mortality in Japan. As both population aging and climate warming are expected to continue, substantial and coordinated adaptation efforts will likely be necessary to mitigate future increases in heat-related deaths.

Similar patterns may also emerge in other countries undergoing parallel demographic and climatic changes, suggesting that heatstroke mortality could become an increasing public health concern in a range of settings. The analytical framework presented in this study provides a foundation for detecting spatial hotspots and temporal shifts in risk, supporting future vulnerability assessments and the design of targeted, evidence-based prevention strategies.

References

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