Exploring the Impacts of Humid Heatwaves on Heat-Related Deaths in India (2001–2022)

Deepali Bidwai [1], Alind Jain [2], Puneet Kollipara [3], Daniel Hagan [4], Kenny T. C. Lim Kam Sian [5]

[1] [2] [3] Independent Researcher
[4] Hydro-Climate Extremes Lab, Ghent University, Ghent, Belgium
[5] School of Atmospheric Science and Remote Sensing, Wuxi University, Wuxi, China

Abstract

In recent years, humid heatwaves have emerged as one of the deadliest forms of climate-induced stress. This study investigates the relationships between humid heatwaves, estimated via wet-bulb temperature (WBT), and heat-related deaths (HRDs) across India from 2001 to 2022. Humid heatwave events are defined as three or more consecutive days during which the wet-bulb temperature exceeds the 90th percentile threshold for each state, based on ERA5 reanalysis data. Using multivariate regression analysis, we find that both heatwave frequency, WBT, and total population significantly predict variations in HRDs at the state level. Spatial analysis reveals an expanding geographic spread of HRDs over time, highlighting emerging vulnerabilities in new regions. These findings highlight the need for localized adaptation strategies that account for population exposure and increasing heatwave intensity.

1. Introduction

Heatwaves are an increasing threat to public health and infrastructure, particularly in densely populated countries like India. These events disproportionately affect vulnerable populations and are expected to intensify with climate change.

While early research focused primarily on dry heat, recent studies highlight the heightened lethality of humid heat, where high temperatures combined with moisture severely limit the body's ability to cool. Wet-bulb temperature (WBT), which captures both heat and humidity, has emerged as a key indicator of heat stress[3].

This study examines how heatwave characteristics—particularly frequency and intensity measured via WBT[1]—along with demographic factors like total population[8], influence heat-related deaths (HRDs) across Indian states between 2001 and 2022. By combining environmental and demographic data, we aim to identify key drivers of heatwave mortality and emerging regional vulnerabilities.

2. Data and Methodology

2.1 Data Sources

We used ERA5 reanalysis data (2001–2022)[6] from the European Centre for Medium-Range Weather Forecasts (ECMWF) to calculate wet-bulb temperature (WBT) using daily maximum temperature (t2m) and dewpoint temperature (d2m). ERA5 provides hourly data at a spatial resolution of 0.25° × 0.25° (~31 km), which we aggregated to daily values for analysis.

Heat-related death (HRD) data, reported annually at the state level, were obtained from the Open Government Data Platform India.

Population-density figures were calculated from WorldPop (100-meter spatial resolution) and LandScan (approximately 1-km spatial resolution). Annual estimates from 2001 to 2022 were used where available; no interpolation was necessary.

All datasets were spatially aggregated to the state level using geospatial joins with official Indian state boundaries, ensuring consistency in spatial alignment across sources.

2.2 Heatwave, WBT and UHI Calculation

WBT Calculation

To estimate humid heat stress, we calculated the WBT using the daily maximum air temperature and dew point temperature from ERA5. WBT was computed using the following empirical[7] approximation formula:

$$\begin{aligned} T_{\mathrm{WB}} = {} & T \tan^{-1}\left(0.151977\sqrt{RH + 8.313659}\right) \\ & + \tan^{-1}(T + RH) - \tan^{-1}(RH - 1.676331) \\ & + 0.00391838 RH^{1.5} \tan^{-1}(0.023101 RH) - 4.686035 \end{aligned}$$

Where:

T_{WB} is the wet bulb temperature (in °C)
T is the temperature (in °C)
RH is the relative humidity (a value between 0 and 100)

Relative humidity (RH) is computed as[9]:

$$RH = 100\frac{e^{\frac{17.625D}{243.04+D}}}{e^{\frac{17.625T}{243.04+T}}}$$

where D is dew point temperature and T is air temperature, both in °C.

All calculations were performed for each grid cell before spatial aggregation to the state level.

2.3 Statistical Analysis

To quantify the impact of environmental and demographic variable on heat-related deaths (HRDs), we employed multivariate linear regression using state-level data from 2001 to 2022. Predictor variables included the number of heatwave days per year, median wet-bulb temperature (WBT), and total population[4]. These predictors were selected to represent distinct aspects of heat exposure and vulnerability.

We reported coefficient estimates, standard errors, R^2 values, and p-values to assess the strength, direction, and significance of associations. To explore potential non-linearities and disproportionate effects, we additionally fitted quadratic models and analyzed residual plots. Statistical analyses were conducted using Python's statsmodels and scikit-learn libraries.

3. Results and Discussion

3.1 Long-Term HRD Trends

The national trend in heat-related deaths (HRDs) from 2001 to 2022 is nonmonotonic, exhibiting two statistically distinct phases. From 2001 to 2015, there was a significant upward trajectory (slope = 63.83 deaths/year, $r = 0.79$, $p < 0.001$), with heatwave days also rising during this period—suggesting that heightened exposure to extreme heat was a key factor driving the increase in HRDs[5]. However, this trend reversed after 2015, with HRDs markedly declining through 2022 (slope = –131.68 deaths/year, $r = -0.77$, $p = 0.044$), even as heatwave days generally continued to rise. (PS: Supplementary Figure 1)
This trend inversion may reflect the impact of early-stage heat action plans, public awareness campaigns, or improved early warning systems. The sharp contrast between these two phases highlights the importance of treating HRDs as a dynamic outcome shaped by both climate change and adaptive interventions.

3.2 Heatwave Characteristics and HRD Correlations

The bivariate relationships between heat-related deaths (HRDs) and three key predictors—heatwave days, wet-bulb temperature (WBT), and total population—reveal that HRDs exhibit a moderate positive correlation with both heatwave frequency ($r \approx 0.22$) and median WBT ($r \approx 0.35$). These associations suggest that extreme heat exposure is a major driver of mortality in India over the study period. The correlation with total population is weaker, indicating that population size alone does not fully explain variations in heat-related deaths without considering vulnerability and exposure. To further quantify these relationships, we conducted a multivariate regression analysis using heatwave days, median WBT, and total population as predictors of HRDs. The results indicate that each additional heatwave day is associated with an increase of 0.56 HRDs ($p = 0.002$), while a 1°C rise in median WBT corresponds to 2.65 additional HRDs ($p < 0.001$). Additionally, each 1-million-person increase in total population is associated with approximately 0.57 additional HRDs ($p < 0.001$). Overall, the model explains 22.6% of the variance in HRDs ($R^2 = 0.226$), indicating a moderate explanatory power.

To explore the disproportionate mortality burden further, we analyzed the number of heat-related deaths per heatwave day. A multi-panel statistical visualization shows that a quadratic fit suggests non-linearity, residuals reveal model misspecification under linear assumptions, and kernel-density estimates and boxplots highlight temporal and regional variation. (PS: Supplementary Figure 3)

3.3: Spatio-Temporal Trends and Regional Vulnerabilities

We analyzed spatial patterns of HRDs, heatwave days, total population, and median WBT across India for key years—2001, 2010, 2020, and 2022 (PS: Supplementary Figure 4). These spatio-temporal plots reveal an increasing geographical spread of heat-related mortality over time, with more states contributing to the national burden.

Several notable trends emerged:

- Andhra Pradesh recorded the highest average annual HRDs across the 22-year period, driven especially by an extreme mortality surge in 2015. This spike was disproportionate to its number of heatwave days, suggesting either inadequate preparedness or an intense, highly localized event.
- Uttar Pradesh, Punjab, Bihar, and Maharashtra ranked among the top five in average HRDs per year, aligning with elevated WBT and increasing heatwave frequency—indicating persistent vulnerability in these populous regions.
- Gujarat, Madhya Pradesh, and Tamil Nadu recorded the highest average number of heatwave days per year, but did not always experience correspondingly high HRDs. This mismatch suggests that heatwave exposure alone does not fully explain mortality, reinforcing the importance of socioeconomic, infrastructural, and other mediating factors.

These findings suggest the following:

- Disproportionate impact: Mortality is not always proportional to heatwave frequency or WBT, highlighting the need to account for healthcare access, warning systems, and urban heat-risk-management measures.
- Widening spread: Heatwave impacts are diffusing geographically, as the number of states with significant HRDs has increased over time.

These patterns justify the need for state-specific, spatially informed strategies to mitigate heatwave impacts, especially under continued climate change and urbanization.

To further examine regional disparities, we analyzed annual trends in HRDs, heatwave days, total population, and WBT for the five most-affected states—Andhra Pradesh, Uttar Pradesh, Bihar, Punjab, and Maharashtra—based on average HRDs over the 2001–2022 period (PS: Supplementary Figure 5).
Andhra Pradesh showed an extraordinary spike in HRDs around 2015 despite moderate heatwave days, highlighting potential deficiencies in local preparedness.
Uttar Pradesh and Bihar exhibited sustained high HRDs aligned with increasing heatwave days and elevated WBT levels, while Punjab demonstrated high mortality despite reporting fewer heatwave days, possibly due to compounding vulnerabilities in healthcare and infrastructure.
In contrast, total population rose gradually across all five states, but alone did not account for mortality trends, emphasizing that exposure must be considered alongside adaptive capacity and vulnerability.

These findings reinforce the urgency of localized, state-specific interventions that address both environmental hazards and demographic sensitivities to reduce future heat-related mortality.

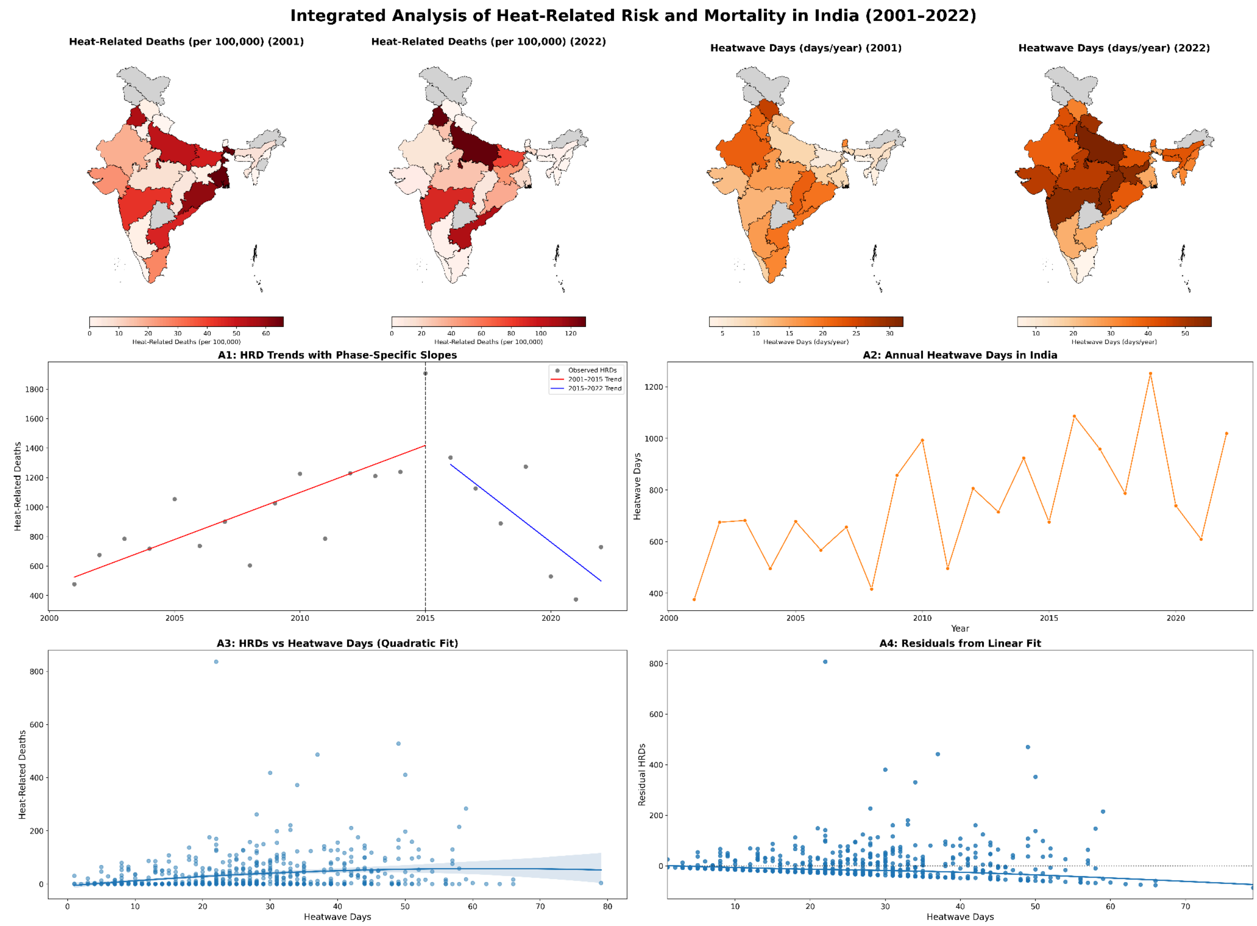

Figure 1. Integrated Analysis of Heat-Related Risk and Mortality in India (2001–2022). Top Panel: *State-wise maps of heat-related deaths (HRDs) and heatwave days for 2001 and 2022. HRDs show a substantial geographic spread over time, with more states contributing to national mortality burden. Heatwave days also increased, especially in central and western India.* ***Middle Panel:*** *National-level temporal trends. Panel A1 shows a statistically significant increase in HRDs from 2001 to 2015, followed by a decline through 2022, suggesting possible effects of adaptation or policy interventions. Panel A2 shows a continuous increase in annual heatwave days across the study period.* ***Bottom Panel:*** *Disproportionate effects of heatwaves on mortality. Panel A3 reveals a non-linear relationship between HRDs and heatwave days, indicating threshold-like impacts. Panel A4 displays residuals from a linear fit, further supporting model nonlinearity and the need to consider additional modifying factors such as infrastructure, preparedness, or healthcare access.*

4. Conclusion and Future Work

4.1 Conclusion

This study examines how humid heatwaves—measured via wet-bulb temperature (WBT)—and associated factors influence heat-related deaths (HRDs) across India between 2001 and 2022. Using state-level data and multivariate regression analysis, we find that both heatwave frequency and WBT are significantly associated with increases in HRDs, with WBT emerging as the strongest predictor. Total population also shows a positive but comparatively weaker association with HRDs, suggesting that while greater population size increases exposure potential, it does not fully explain the observed variations in heat-related mortality.

Temporal analysis reveals two distinct phases: an upward trend in HRDs until 2015, followed by a national decline thereafter. Spatio-temporal mapping further indicates a widening geographical spread of heat risk, with new states becoming increasingly vulnerable over time.

Notably, states such as Himachal Pradesh, Uttarakhand, and Goa consistently exhibited low HRD rates despite climate and demographic variability. These patterns suggest that factors such as lower baseline temperatures, distributed populations, proactive adaptation measures, or strong public health systems may offer protective effects against heat-related mortality.

Although urban heat island (UHI) intensity[11][12] was initially examined as a potential modifier of heat-related deaths, our analysis found limited or inconsistent associations at the state level. This may partly reflect the coarse spatial resolution of HRD reporting, which aggregates deaths at the state scale rather than within localized urban centers where UHI effects are strongest. Future studies with city-specific mortality data and finer urban characterization are needed to fully disentangle the role of UHI in shaping heatwave impacts.

Together, these findings emphasise that heatwave impacts are shaped by a complex mix of environmental, demographic, and infrastructural factors, and that aggregated national metrics can obscure critical local patterns. Adaptation strategies must be targeted, spatially informed, and sensitive to regional disparities.

4.2 Future Work

To build upon these insights and improve heatwave risk assessment, future studies should:

- Integrate socioeconomic indicators such as income, age brackets, occupation, and healthcare access.
- Analyze the effectiveness of adaptation measures, such as state-level heat-action plans, early-warning systems, and cooling interventions.
- Incorporate higher-resolution urban land-cover/land-use and urban climate data (e.g., city-level LST, vegetation or tree-canopy cover, and impervious surface cover) to quantify intra-urban UHI and exposure heterogeneity.
- Integrate remote sensing-derived vegetation, water and built-environment indices (e.g., NDVI, NDWI, MSAVI2, NDBI) to better quantify the role of urban greenery, soil moisture, agricultural cover and buildings in modulating heatwave impacts. Vegetation buffers, in

particular, are critical mediators of local thermal regimes. Incorporating such indices would enable finer-grained risk assessments.

- Develop and test predictive models (e.g., regression, machine learning) to estimate heat-related deaths (HRDs) based on heatwave and UHI indicators, both individually and combined. Doing so would inform assessments of the relative predictive power of each factor at the national and state levels, offering insights into targeted interventions.
- Validate findings with health-surveillance data, such as hospitalization rates or cause-of-death certificates, to strengthen epidemiological links.

Ultimately, mitigating heatwave mortality in India will require a combination of spatial risk forecasting, public-health readiness, and urban-planning changes, particularly in the face of continued climate intensification and rapid urban expansion.

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Supplementary Figures

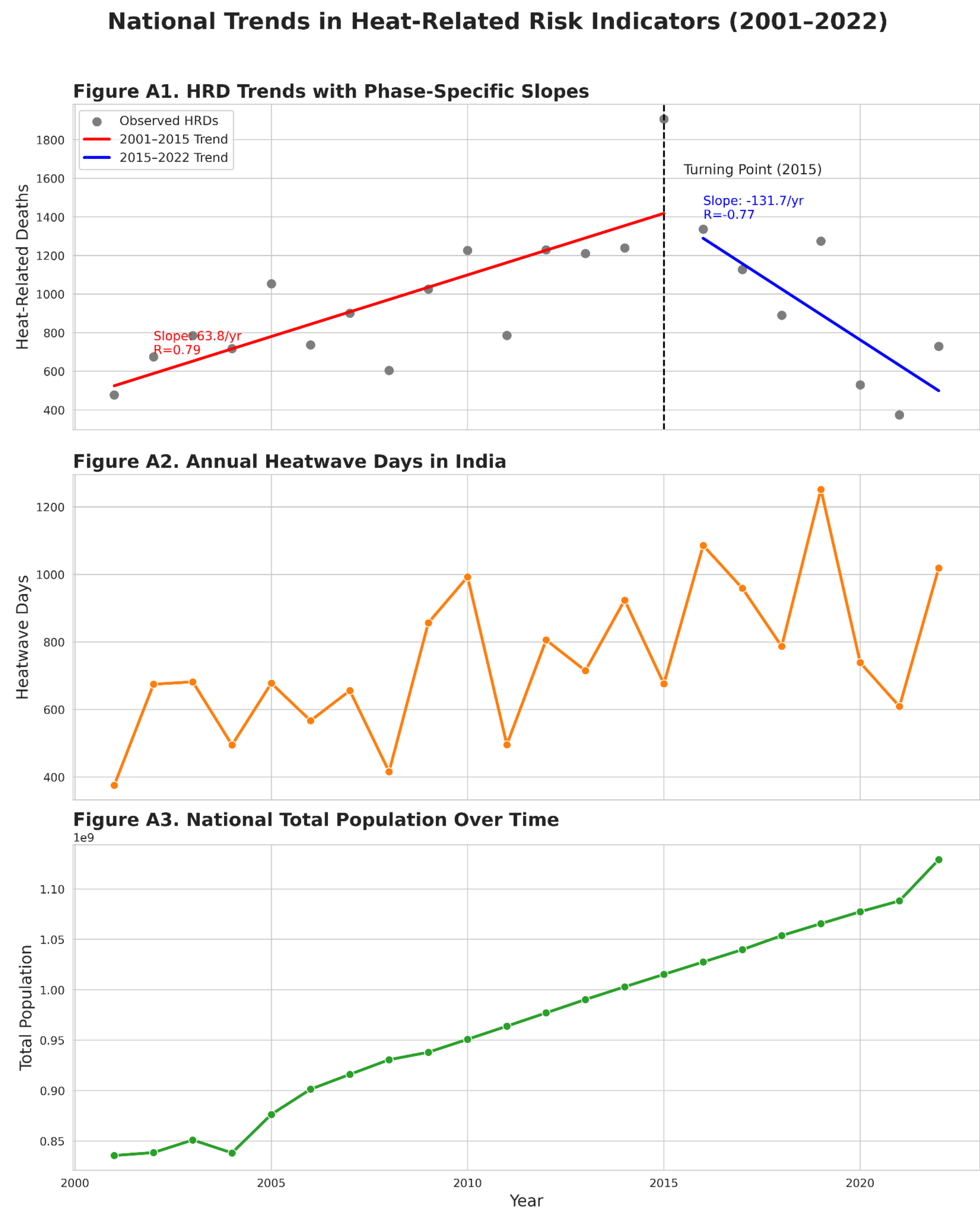

Figure 1. National-level temporal trends in heat-related deaths (HRDs), heatwave days, and population density in India (2001–2022). *Panel (A1) distinguishes two significant phases in HRDs: an upward trend from 2001–2015 and a decline from 2015–2022. Panel (A2) shows a gradual increase in the*

frequency of heatwave days. Panel (A3) displays rising total population, reflecting growing exposure potential.

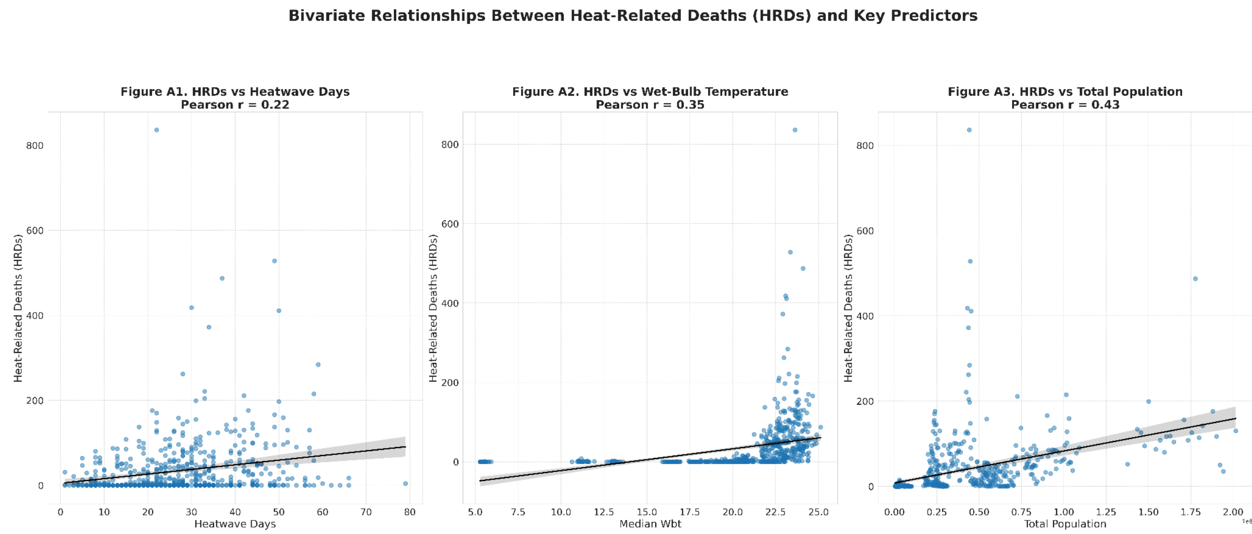

Figure 2. Bivariate relationships between heat-related deaths (HRDs) and key predictors across Indian states (2001–2022). *The scatter plots show the correlations between: (A1) Heatwave days: HRDs increase moderately with the frequency of heatwaves. (A2) Median wet-bulb temperature (WBT): HRDs increase significantly with rising WBT, indicating a strong relationship between heat stress and heat-related mortality. (A3) Total population: HRDs show a weaker positive association with population size, suggesting that while larger populations are associated with more HRDs, this effect is relatively small compared to heatwave days and WBT.*

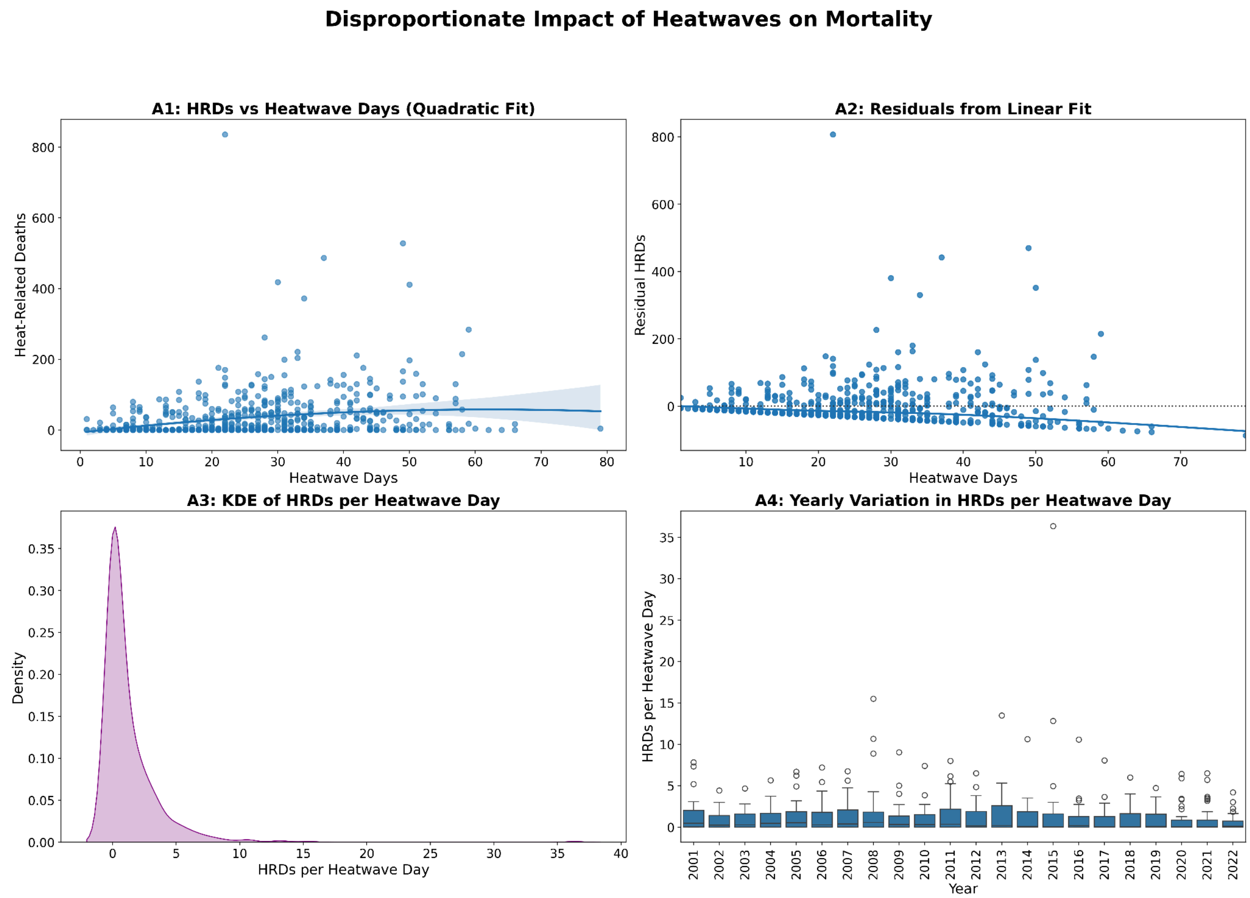

Figure 3. Disproportionate impacts of heatwaves on mortality across India (2001–2022). *(A1) HRDs vs. heatwave days with a fitted quadratic curve. (A2) Residuals from a linear regression model showing non-linear deviation. (A3) Kernel density estimate (KDE) of HRDs per heatwave day, highlighting skewness. (A4) Boxplot of HRDs per heatwave day across years showing interannual variation.*

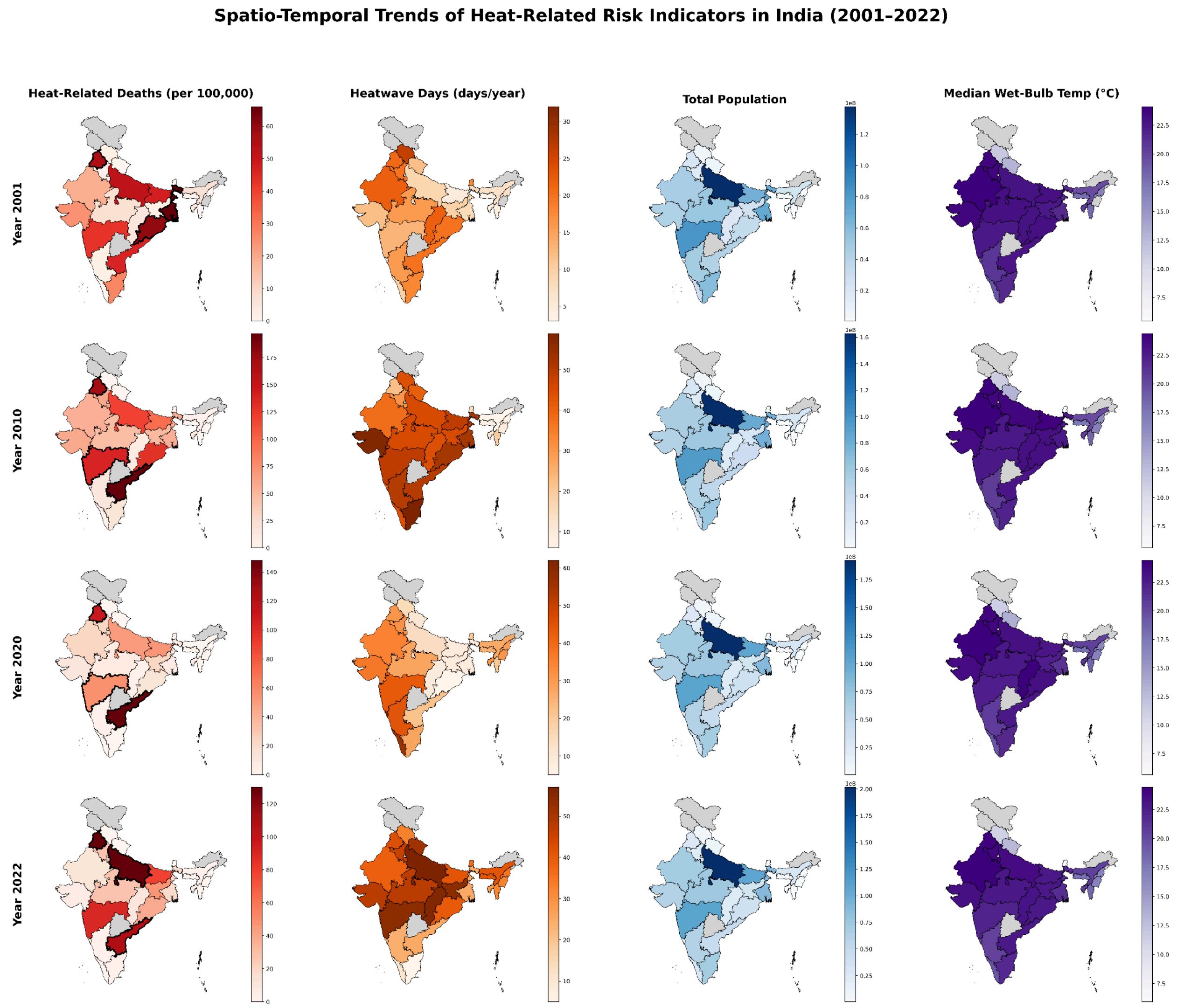

Figure 4. Spatio-temporal expansion of heat risk indicators across Indian states (2001–2022). *Each panel shows state-wise values of key variables: heat-related deaths (HRDs), heatwave days, total population, and median wet-bulb temperature (WBT) for selected years (2001, 2010, 2020, and 2022).*

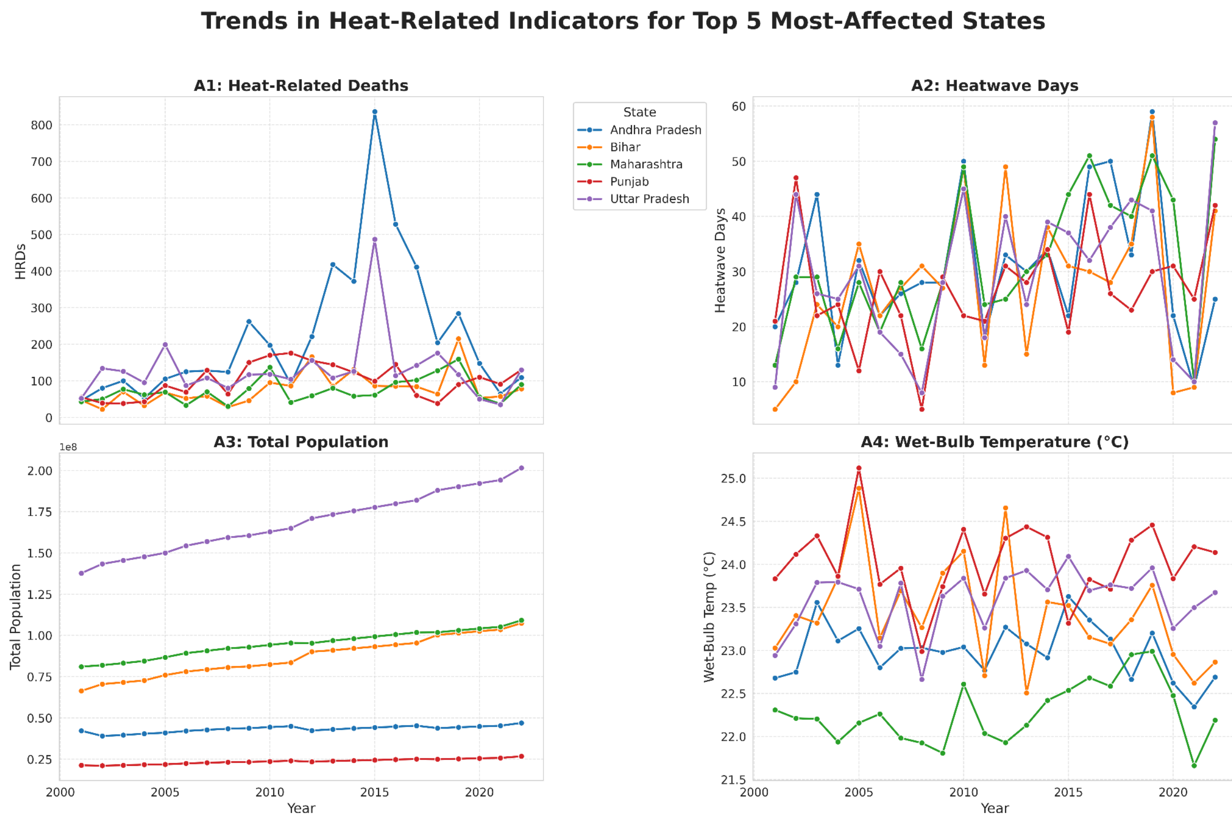

Figure 5. Trends in Heat-Related Risk Indicators for Top 5 Most-Affected States (2001–2022). *The panels show temporal patterns for heat-related deaths (HRDs), heatwave days, total population, and median wet-bulb temperature (WBT) for Andhra Pradesh, Uttar Pradesh, Bihar, Punjab, and Maharashtra, the five states with the highest average HRDs.*