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Soundarya Soundararajan
ICMR-National Institute of Occupational Health
Bhavani Shankara Bagepally
ICMR-National Institute of Epidemiology
Jhalak Dhingra
ICMR-National Institute of Occupational Health
Nimitha Mohan
ICMR-National Institute of Epidemiology
Bhavesh Modi
ICMR-National Institute of Occupational Health
Rakesh Balachandar
rakesh.bal@icmr.gov.in

ICMR-National Institute of Occupational Health

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Heat Index Exposure and Cardiovascular Disease Burden in India: Population-Attributable Risk and Economic Implications

Soundarya Soundararajan*[1], Bhavani Shankara Bagepally*[2], Jhalak Dhingra[1], Nimitha Mohan[2], Bhavesh Modi[1], Rakesh Balachandar[1#]

[1] ICMR-National Institute of Occupational Health, Ahmedabad, India

[2] ICMR-National Institute of Epidemiology, Chennai, India

* Both authors contributed equally and may be deemed as first authors.

Corresponding author

Address for correspondence:

ICMR-National Institute of Occupational Health Meghaninagar,

Ahmedabad, 380016, India.

balachandar.rakesh@gmail.com

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Abstract

Background: Climate change is intensifying heat exposure in South Asia, yet the population-level cardiovascular disease (CVD) burden attributable to Heat Index (HI) exposure in India remains unquantified.

Methods: We analyzed state-level panel data (29 states, 2011–2021) linking ERA5-derived HI metrics with Global Burden of Disease CVD outcomes (DALYs, YLL, YLD). Log-linear fixed-effects panel regression models estimated the percent change in CVD burden per unit increase in HI, adjusting for state and year fixed effects. The population-attributable fraction (PAF) was calculated using a model-based counterfactual approach with the 80th percentile of observed HI as the reference threshold. State-specific economic burden was estimated by multiplying attributable DALYs by cost-per-DALY values and projected to 2030 using ARIMA and 3% annual cost growth.

Results: A one-unit increase in the 97.5th percentile of average HI was associated with a 1.62% (95% CI: 0.67%, 2.57%) increase in CVD DALYs and a 1.7% (0.7%, 2.7%) increase in YLL. The PAF at the 80th percentile threshold was 0.28%, corresponding to approximately 206,000 attributable DALYs in 2021 and an economic burden of approximately INR 1,485 Crore (~USD 199 million). By 2030, the projected economic burden was approximately INR 2,174 Crore (~USD 292 million), a 46% increase.

Conclusions: Extreme HI exposure is associated with a measurable fraction of India's CVD burden that translates to a substantial and growing economic cost. These state-level estimates can inform the prioritization of heat–health interventions in India.

Keywords: Heat Index; Cardiovascular disease; Economic burden; Climate Change; India

Introduction

Climate change and cardiovascular disease (CVD) are both intersecting global public health challenges. A systematic review and meta-analysis of 266 studies reported that each 1°C increase in temperature was associated with a 2.1% increase in CVD mortality risk. Extreme events like the heatwaves, further intensify this to an 11.7% increase in risk [1]. Having experienced several heatwaves in recent decades including fatal ones, South Asis is highly vulnerable to extreme heat [2,3]. Projections indicate that heatwave frequency, duration, and intensity in the region will continue to escalate, with wet-bulb temperatures approaching human survivability limits even at 1.5°C of global warming [2]. This trajectory poses a growing threat to population health, particularly through its effects on the cardiovascular system.

In this juncture, it is only imperative to assess how populations experience thermal stress when reflecting on climate exposures metrics. Epidemiological studies have documented associations between humid heat conditions and adverse cardiovascular outcomes, including higher mortality during high-temperature and high-humidity exposures [4] and a causal link between humid heatwaves and ischaemic heart disease [5]. Heat grapples its effects on the cardiovascular health through multiple physiological pathways: thermoregulatory demands during sustained heat stress increase cardiac output, accelerate heart rate, and reduce blood pressure, that can precipitate dehydration, cardiac arrhythmias, and acute cardiovascular events [6]. Heat Index variable, that

integrates temperature and humidity into a single metric, can more closely reflect this physiological heat strain than temperature alone [7].

India faces a particularly acute convergence of heat exposure and rising CVD burden. Elevated temperatures have been linked to approximately 3.3% of CVD deaths in the country, and unit increases in average temperature have been associated with higher national CVD burden [8]. Projection scenario under a 2°C warming scenario depict that heatwaves may become 30-fold more frequent [9]. Concurrently, CVD is the leading cause of death and disability in India, accounting for a substantial proportion of total disability-adjusted life years (DALYs) [10]. Despite India's marked spatial variability in humid-heat exposure driven by monsoon patterns, the contribution of Heat Index to cardiovascular disease burden has not been systematically quantified. Moreover, most climate-CVD studies focus on mortality or hospital admissions, and there is limited probing of comprehensive burden measures such as DALYs, particularly in low- and middle-income countries [1].

The economic implications of heat-related cardiovascular burden are also not well characterized. The population-attributable fraction (PAF) of CVD DALYs linked to Heat Index exposure has not been estimated for India, and no study to date has translated heat-attributable CVD DALYs into monetary terms at the state level. Although state-level panel analyses linking environmental exposures to DALY-based economic losses have been applied in India for air pollution [11], studies linking apparent temperature or humidity exposures with DALY-based economic losses remain scarce, limiting evidence for climate-resilient health planning and resource prioritization [12,13].

To address these gaps, we conducted a national-scale panel analysis across Indian states from 2011 to 2021 to examine the association between the Heat Index and CVD burden. Specifically, we quantified relationships between multiple Heat Index metrics, including measures of extremes and variability and CVD-related disability-adjusted life years (DALYs), years of life lost (YLL), and years lived with disability (YLD) using state-level fixed-effects regression models. We then estimated the Heat Index–attributable CVD burden and corresponding economic costs for 2021 and projected these estimates to 2030; in doing so, we characterized spatial patterns of vulnerability to inform climate-resilient cardiovascular health planning in India.

Materials and Methods

Data Sources

Climate Data

The current study utilized archived temperature and relative humidity data sourced from ERA5, the fifth-generation atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) [14]. ERA5 offers hourly estimates of climate variables at a regular latitude-longitude grid interval of 0.25° (approximately 30 km). These temperature and humidity data were used exclusively for calculating the Heat Index, the primary climate exposure variable in this study.

Cardiovascular Disease Burden

Cardiovascular disease burden estimates were sourced from the Global Burden of Disease (GBD) repository [10], state-wise. We extracted state-level, year-wise data for

three CVD burden metrics: disability-adjusted life years (DALYs), years of life lost (YLL), and years lived with disability (YLD) for the period 2011–2021. Two versions of the GBD data were used: population-corrected rates (per 100,000 population) for regression analysis, and absolute counts for economic burden calculation.

Cost per DALY

State-specific cost-per-DALY (CpD) estimates for CVD in India for the year 2021 were obtained from a prior analysis by Bagepally et al. [15], in which a panel regression framework was used to relate per-capita CVD DALYs to per-capita CVD health expenditure from 2011 to 2021.

Data Processing

Climate Data Extraction and Heat Index Calculation

Using the bounding box coordinates of Indian states, we extracted gridded data for temperature and relative humidity from the ERA5 dataset. Data values from coordinates within the bounding box of each state were aggregated to represent the climate variables of that state.

We collected hourly recordings of two-meter temperature and relative humidity data from the ERA5 database for every day between 00:00 h on 1 January 2011 and 23:00 h on 31 December 2021. Heat Index values were derived by combining the temperature and relative humidity data using the wet bulb temperature formula proposed by Stull (2011) [7]:

HI

$$= T \times \arctan\left[0.151977 \times \sqrt{RH + 8.313659}\right] + \arctan(T + RH) - \arctan(RH - 1.676331)$$
$$+ 0.00391838 \times RH^{3/2} \times \arctan(0.023101 \times RH) - 4.686035$$

where T is the air temperature in degrees Celsius and RH is the relative humidity in percentage. This empirical formula is valid for relative humidities between 5% and 99% and air temperatures between –20°C and 50°C at standard sea level pressure (101.325 kPa). The Heat Index represents the combined effect of temperature and humidity on human thermal comfort and heat stress.

Daily Summaries and Percentile Extraction

We aggregated the hourly Heat Index values into six daily summary variables: average (mean of 24 hourly values), median, mode, maximum, minimum, and variation (difference between maximum and minimum for each day) for every available coordinate. Then we averaged them across the coordinates to obtain single value for the state. These values were then sorted to obtain extreme values, low (2.5th percentile) and high (97.5th percentile) for each of the six Heat Index summary variables were identified for each state-year. This yielded 12 Heat Index summaries (two percentile measures for six summary variables) per state per year, which served as the predictor variables. State-wise temporal trends in average Heat Index and Heat Index variation across the study period are presented in Supplementary Figures S2a and S2b.

Cardiovascular Disease Data Integration

Year-wise, state-wise population-corrected DALY, YLL, and YLD data for all cardiovascular diseases were extracted from the GBD and matched against the Heat Index summaries by state and year. The state of Jammu & Kashmir, which was reorganized as two separate union territories subsequent to 2019, was excluded from the analysis owing to data availability constraints.

Statistical Analysis

Statistical analysis employed a multi-stage approach.

Stage 1: Variable Selection

Pearson correlation analysis was conducted to assess multicollinearity among the 12 Heat Index summary variables. Based on the correlation structure (Supplementary Figure S1), three Heat Index metrics were selected for regression modelling to reduce redundancy while preserving interpretability of heat exposure extremes: average Heat Index at the 97.5th percentile (avg_97.5), Heat Index variation at the 2.5th percentile (var_2.5), and Heat Index variation at the 97.5th percentile (var_97.5).

Stage 2: Panel Regression Modelling

To estimate the association between Heat Index exposure and CVD burden, we fitted log-linear fixed-effects panel regression models separately for each combination of Heat Index metric and CVD outcome (DALY, YLL, YLD) across Indian states from 2011 to 2021. The model specification was:

$$\log(Y_{it}) = \beta_0 + \beta_1 \cdot \mathrm{HI}_{it} + \gamma_t + \alpha_i + \varepsilon_{it}$$

where Y_{it} denotes the CVD outcome (per 100,000 population) for state i in year t; HI_{it} is the Heat Index metric of interest; α_i captures unobserved, time-invariant state-level heterogeneity (state fixed effects); and γ_t captures year fixed effects. Models were estimated using the pglm package in R with a Gaussian family, within-state (fixed-effects) specification, and the Broyden–Fletcher–Goldfarb–Shanno (BFGS) optimisation method.

Regression coefficients were exponentiated and expressed as percent changes in CVD burden, calculated as $\left(\exp\left(\hat{\beta}_1\right) - 1\right) \times 100$, with 95% confidence intervals derived similarly. These estimates represent the within-state percent change in DALY, YLL, or YLD associated with a one-unit increase in the Heat Index metric, adjusting for year fixed effects. Statistical significance was assessed at a two-sided p-value threshold of 0.05.

Stage 3: Population-Attributable Fraction

The population-attributable fraction (PAF) was estimated using a model-based counterfactual prediction approach. This approach quantifies the proportion of CVD burden associated with Heat Index exposure by comparing predicted outcomes under observed conditions with predictions under a defined counterfactual exposure scenario.

The primary counterfactual reference was set at the 80th percentile of the observed national distribution of average Heat Index (avg_97.5) over the study period, consistent with the range at which minimum mortality risk has been identified in heat-health literature [16,17]. This threshold represents the transition from moderate to high heat exposure.

The PAF was calculated as:

$$\text{PAF} = 1 - \frac{\sum_i Y_i \cdot \exp\left[\hat{\beta}_1 \cdot (\tilde{x}_i - x_i)\right]}{\sum_i Y_i}$$

where x_i denotes the observed Heat Index exposure for observation i; $\tilde{x}_i = \min(x_i, x_{\text{ref}})$ is the counterfactual exposure capped at the reference threshold x_{ref}; Y_i is the observed CVD DALY; and $\hat{\beta}_1$ is the regression coefficient for avg_97.5. This formulation estimates the proportion of CVD DALYs that would theoretically be avoided if extreme Heat Index exposure were reduced to the reference threshold, under the assumption that the modelled association is stable.

Economic Analysis

Baseline Economic Burden (2021)

State-specific attributable CVD DALYs for 2021 were computed by applying the PAF to absolute (population-uncorrected) GBD CVD DALY counts:

$$\text{Attributable DALYs}_s = \text{CVD DALYs}_{s,2021} \times \text{PAF}$$

The economic burden for each state was estimated by multiplying attributable DALYs by the state-specific CpD for 2021 (obtained from Bagepally et al.[15]):

$$\text{Economic burden}_{s,2021} = \text{Attributable DALYs}_s \times \text{CpD}_{s,2021}$$

All costs were expressed in constant 2021 Indian Rupee (INR) values. For international comparability, USD equivalents were computed using the 2021 annual average exchange rate of 1 USD = 74.5 INR.

Projected Economic Burden (2030)

Future state-specific CVD DALYs were projected from the observed 2011–2021 time series to 2030 using autoregressive integrated moving average (ARIMA) models. For each state, the optimal ARIMA specification was selected automatically based on the Akaike Information Criterion. The 2030-point forecasts were used for subsequent calculations.

CpD was projected from 2021 to 2030 by applying a compound annual growth rate (CAGR) of 3%:

$$\text{CpD}_{s,2030} = \text{CpD}_{s,2021} \times (1.03)^9$$

The PAF estimated from the 2011–2021 data was applied to the projected 2030 CVD DALYs, assuming that the relative contribution of Heat Index exposure to CVD burden remains constant over time. This assumption reflects a status quo vulnerability scenario and does not account for potential changes in heat exposure intensity, population susceptibility, or adaptive capacity.

The projected economic burden was then calculated as:

$$\text{Economic burden}_{s,2030} = \left(\text{Projected DALYs}_{s,2030} \times \text{PAF}\right) \times \text{CpD}_{s,2030}$$

Spatial Visualization

State-level attributable DALYs and economic burden estimates were mapped using administrative boundary shapefiles for India to visualize geographic variation.

Software

All statistical analyses and visualizations were conducted in R version 4.3.2 [18]. Key packages included *pglm* for panel regression, *forecast* for ARIMA modelling, *sf* for spatial analysis, and *ggplot2* and *tidyverse* for data manipulation and visualization. The analysis pipeline was implemented as a reproducible Quarto document.

Results

Panel Regression Analysis

The analysis included 319 state-year observations across 29 Indian states over 11 years (2011–2021). Log-linear fixed-effects panel regression models were fitted for each combination of three Heat Index metrics and three CVD outcomes (Table 1).

The 97.5th percentile of average Heat Index (avg_97.5) was positively and significantly associated with both CVD DALYs and YLL. Each one-unit increase in avg_97.5 was associated with a 1.62% (0.67%, 2.57%) change in CVD DALYs and a 1.7% (0.7%, 2.7%) change in YLL, after adjusting for state and year fixed effects. The association with YLD was not statistically significant (-0.01% (-0.31%, 0.28%)).

Among the variation metrics, the 97.5th percentile of daily Heat Index variation (var_97.5) showed a significant positive association with YLD (0.32% (0.04%, 0.59%)), but not with DALY or YLL. The 2.5th percentile of variation (var_2.5) was not significantly associated with any CVD outcome. In total, 3 of the nine predictor–outcome combinations reached statistical significance at the 0.05 level.

Population-Attributable Fraction

Using the model-based counterfactual approach with the 80th percentile of the national avg_97.5 distribution as the reference threshold, the estimated population-attributable fraction (PAF) for CVD DALYs was 0.28%. This indicates that approximately 0.28% of India's CVD DALY burden during 2011–2021 was associated with exposure to extreme Heat Index levels above this threshold.

Attributable CVD Burden (2021)

Applying the PAF of 0.28% to absolute state-level CVD DALY counts for 2021 yielded a total of approximately 206,258 DALYs attributable to high Heat Index exposure across 29 states (Figure 1; Supplementary Figure S3 and Table S1). The geographic distribution of attributable DALYs showed substantial variation across states, with the highest absolute burden concentrated in states with large populations and high CVD prevalence.

The total economic burden attributable to Heat Index–associated CVD in 2021 was estimated at INR 14,849,263,459 (approximately INR 1485 Cr or USD 199 million) across 29 states for which cost-per-DALY data were available (Figure 2; Supplementary Table S1). This estimate was obtained by multiplying state-specific attributable DALYs by state-specific CpD values for 2021.

Projected Burden (2030)

ARIMA-based projections of state-level CVD DALYs to 2030, combined with the PAF estimate, yielded a projected total of approximately 236,997 attributable DALYs (Figure 3; Supplementary Figure S4 and Table S2). The geographic pattern of projected attributable burden broadly mirrored that observed in 2021, with the largest absolute increases expected in states that already carried the highest burden.

The projected total economic burden for 2030, incorporating CpD values inflated at a 3% compound annual growth rate, was estimated at INR 21,738,632,670 (approximately INR 2174 Cr or USD 292 million), representing an increase of approximately 46.4% over the 2021 estimate (Figure 4). This increase reflects both the projected rise in CVD DALYs and the anticipated growth in healthcare costs.

Discussion

This study estimated the association between extreme Heat Index exposure and cardiovascular disease burden across Indian states from 2011 to 2021 and translated that association into population-attributable DALYs and economic costs. The principal finding was that a one-unit increase in the 97.5th percentile of average Heat Index was associated with a 1.62% (0.67%, 2.57%) increase in CVD DALYs, corresponding to a PAF of 0.28% when extreme exposures were benchmarked against the 80th percentile threshold. Applied to 2021 GBD data, this yielded approximately 206,258 attributable DALYs and an economic burden of approximately INR 1485 Cr (USD 199 million), projected to rise to INR 2174 Cr (USD 292 million) by 2030, an increase of 46.4%.

The magnitude of the estimated percent change in CVD DALYs per unit Heat Index increase is broadly consistent with the global literature on heat–cardiovascular associations. Yet, direct comparisons are challenging owing to the differences in exposure metrics, outcome definitions, and analytic frameworks in various studies. A systematic review reported that each 1°C rise in temperature was associated with a 2.1% increase in CVD mortality [1], and multi-country analyses have estimated that heat accounts for a small but measurable fraction of cardiovascular deaths in tropical settings

[17,19]. Although the population-attributable fraction of 0.28% we estimated appears modest, applying it to India's substantial CVD burden yields a considerable number of attributable DALYs and corresponding economic losses. To our knowledge, this is among the first estimates translating heat-attributable CVD burden into state-level economic terms for India.

The observed pattern of associations, significant for DALYs and YLL but not for YLD with average Heat Index, suggests that extreme heat exposure may be more strongly linked to fatal and life-shortening cardiovascular events than to non-fatal disability. This is consistent with the understanding that acute heat stress triggers cardiovascular emergencies such as myocardial infarction and arrhythmia that contribute primarily to mortality [16]. These findings complement evidence that other environmental and behavioural factors, including circadian rhythm disruption, are also associated with elevated cardiovascular risk factors such as diabetes and glycaemic dysregulation [20]. In contrast, we found that the 97.5th percentile of daily Heat Index variation was significantly associated with YLD, but not with DALYs or YLL; this pattern may indicate a distinct pathway whereby large diurnal fluctuations in thermal stress exacerbate chronic cardiovascular conditions and increase morbidity without necessarily increasing mortality, potentially through repeated hemodynamic strain [21]. These differential associations warrant further investigation with cause-specific and age-stratified analyses.

The economic framing of heat-attributable CVD burden has direct policy relevance. The estimated cost of INR 1485 Cr in 2021(USD 199 million), projected to grow to INR 2174 Cr (USD 292 million) by 2030, provides a benchmark against which investments in heat action plans and early warning systems can be evaluated. India's experience with the

Ahmedabad Heat Action Plan, which was associated with a measurable reduction in heat-related mortality [22], demonstrates that such interventions are feasible in the Indian context. Moreover, the state-level variation in attributable burden shown in Figures 1 and 3 indicates that intervention priorities should be tailored to local conditions, taking into account both climatic exposure and the underlying prevalence of CVD.

Several limitations should be acknowledged. First, this is an ecological study in which state-year served as the unit of analysis; associations observed at this level cannot be attributed to individual-level exposures, and the possibility of ecological bias cannot be excluded. Second, the fixed-effects panel design adjusts for time-invariant state characteristics and national temporal trends, but residual confounding from time-varying state-level factors, such as urbanization, changes in healthcare access, or air pollution, remains possible. Third, the PAF was calculated using a single counterfactual threshold (80th percentile), and the choice of reference point influences the magnitude of the attributable fraction. While this threshold is supported by heat–health literature identifying minimum mortality temperatures in the 70th–80th percentile range [16, 17], alternative thresholds would yield different estimates. Fourth, the 2030 projections assumed that the PAF remains constant over time and applied a uniform 3% annual growth rate to CpD, assumptions that may not hold if adaptation measures are implemented or if the heat–CVD relationship changes with population ageing and urbanization. Fifth, the exclusion of Jammu & Kashmir and the reliance on bounding-box averaging for climate data introduce some spatial imprecision. Finally, the ERA5 reanalysis data, while globally consistent, may not fully capture localized heat island effects in urban areas where CVD burden is concentrated.

Nevertheless, this study has several strengths. It uses an 11-year state-level panel spanning all major Indian states, a well-validated reanalysis climate dataset, and standardized GBD outcome measures, ensuring broad geographic coverage and temporal depth. The log-linear fixed-effects specification provides within-state estimates that are robust to time-invariant confounders. The model-based counterfactual PAF approach directly quantifies the burden attributable to exposure above a defined threshold, and the economic translation using state-specific CpD estimates from an independent analysis adds policy-relevant context.

Conclusions

Extreme Heat Index exposure was significantly associated with increased CVD DALYs and YLL across Indian states from 2011 to 2021. The population-attributable fraction, though small in percentage terms (0.28%), corresponded to approximately 206,258 attributable DALYs and an economic burden of approximately INR 1485 Cr (USD 199 million) in 2021, projected to rise to INR 2174 Cr (USD 292 million) by 2030. These estimates provide an evidence base for integrating cardiovascular health considerations into heat adaptation planning in India. Future research incorporating finer spatial and temporal resolution, individual-level exposure assessment, and cause-specific CVD outcomes will strengthen the evidence linking Heat Index exposure to cardiovascular burden.

Data availability statement

The ERA5 reanalysis data are publicly available from the Copernicus Climate Data Store (https://cds.climate.copernicus.eu/). The Global Burden of Disease data are available

from the Institute for Health Metrics and Evaluation (https://vizhub.healthdata.org/gbd-results/).

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Authors' Contributions

RB and BSB conceptualized the study. SS led the data analysis and drafted the initial manuscript. BSB provided methodological oversight and critical revisions. JD and NM assisted in data collection and management. RB, BSB and SS designed the analytical framework contributed to data interpretation and all authors approved the final version of the manuscript.

Ethics Approval and Consent to Participate

This study used publicly available, de-identified aggregate data from the Global Burden of Disease repository and ERA5 reanalysis. No individual-level human participant data was collected or analyzed; therefore, ethical approval was not required.

Clinical trial number

Not applicable.

Consent for Publication

Not applicable.

Conflict of Interest statement

The authors declare that they have no competing interests.

Figure Legends

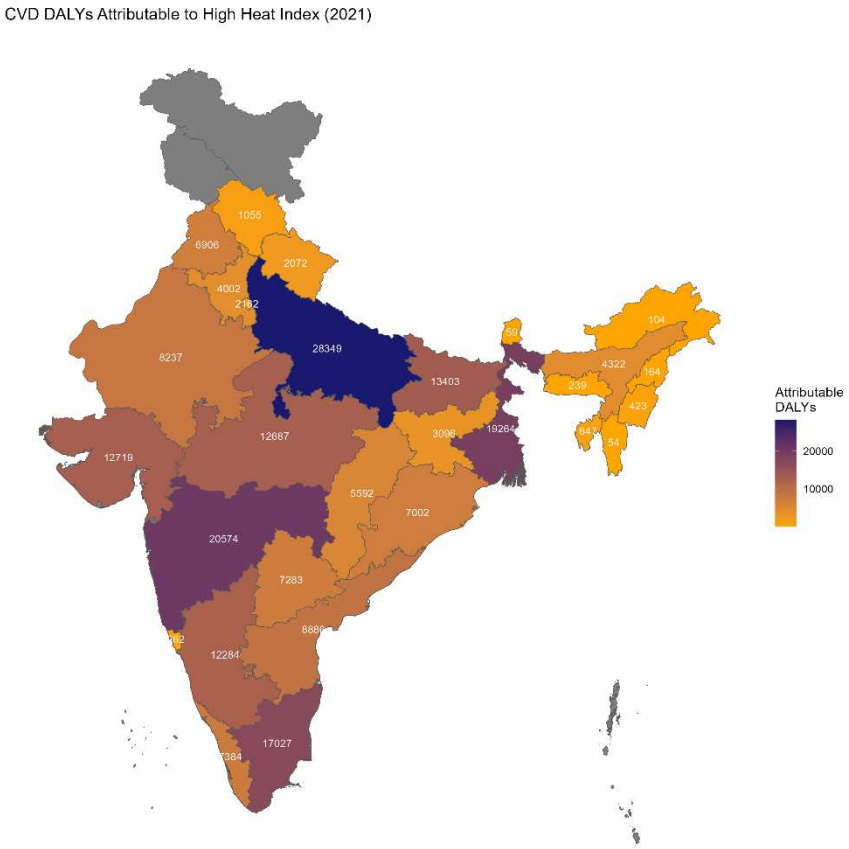


Figure 1.

State-Wise CVD DALYs Attributable to High Heat Index Exposure in India, 2021

Note. Choropleth map displaying the spatial distribution of cardiovascular disease (CVD) disability-adjusted life years (DALYs) attributable to high Heat Index (HI) exposure across 29 Indian states for the year 2021. Attributable DALYs were derived by applying the population attributable fraction (PAF = 0.28%) to state-level absolute CVD DALY counts from the Global Burden of Disease (GBD) 2021 dataset. The PAF was estimated from a log-linear fixed-effects panel regression of the 97.5th percentile of average HI on CVD

DALYs, using the 80th percentile of HI as the counterfactual threshold. State-level values are displayed at each state's geographic centroid. The colour gradient ranges from light (lower burden) to dark (higher burden). States with the largest attributable burden include Uttar Pradesh (28,349), Maharashtra (20,574), and West Bengal (19,264).

DALY = disability-adjusted life year; CVD = cardiovascular disease; HI = Heat Index; PAF = population attributable fraction; GBD = Global Burden of Disease.

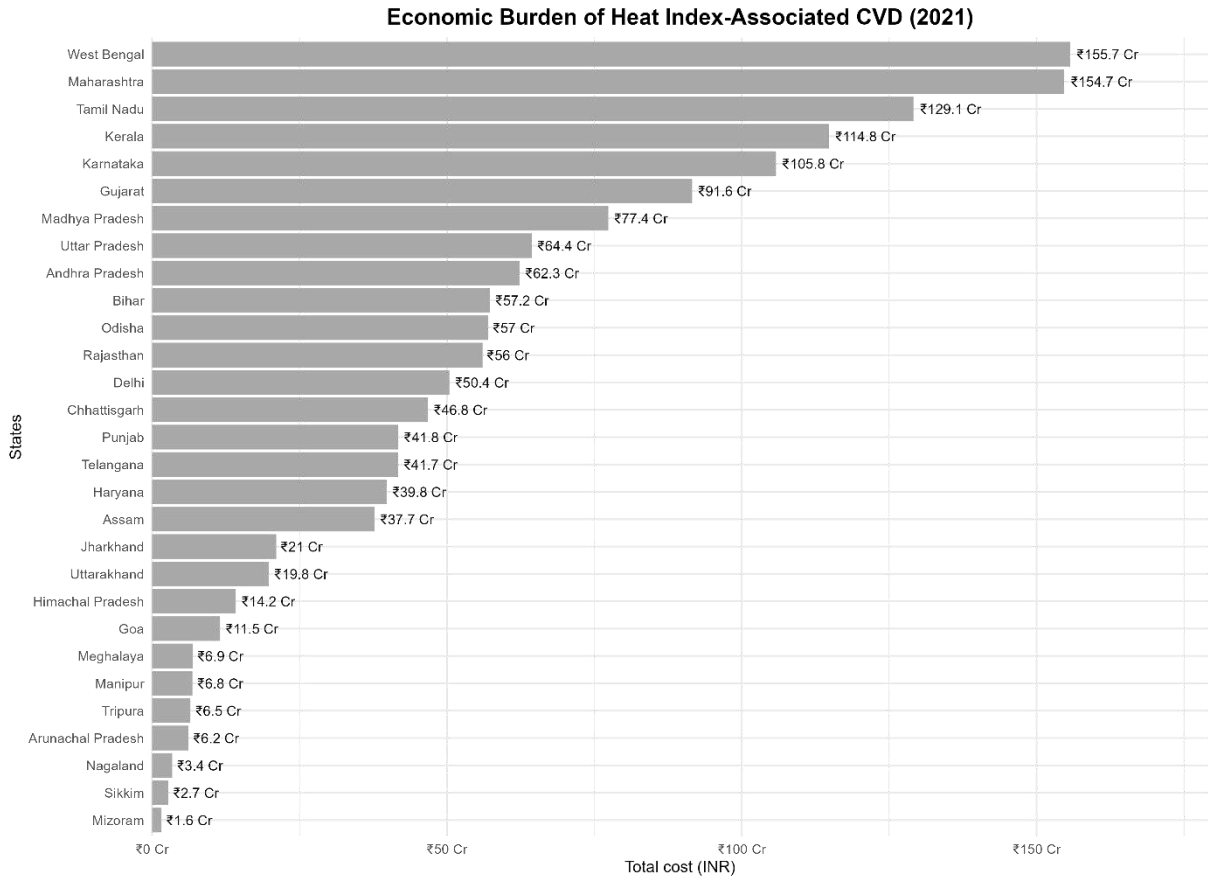


Figure 2.

State-Wise Economic Burden of Heat Index-Attributable CVD in India, 2021

Note. Horizontal bar chart showing the total economic burden (in INR Crore) of cardiovascular disease (CVD) DALYs attributable to high Heat Index (HI) exposure for each Indian state in 2021. Economic burden was computed as the product of state-wise attributable DALYs (PAF-adjusted) and the corresponding state-level cost per DALY. States are ordered by descending magnitude. West Bengal had the highest economic burden, followed by Maharashtra and Kerala. The national total was approximately INR 1,485 Crore (~USD 199 million at the 2021 annual average exchange rate of 1 USD = 74.5 INR).

INR = Indian Rupee; Cr = Crore (10 million); DALY = disability-adjusted life year; CVD = cardiovascular disease; HI = Heat Index; PAF = population attributable fraction; CpD = cost per DALY.

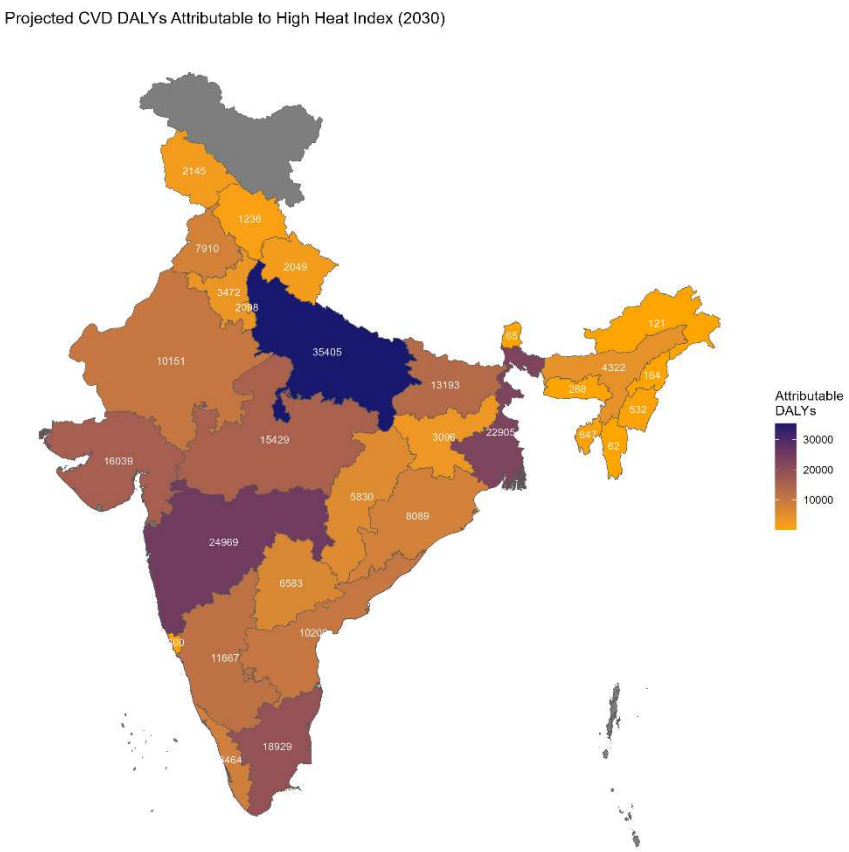


Figure 3

Projected State-Wise CVD DALYs Attributable to High Heat Index Exposure, 2030

Note. Choropleth map displaying the projected spatial distribution of cardiovascular disease (CVD) disability-adjusted life years (DALYs) attributable to high Heat Index (HI) exposure across Indian states for the year 2030. State-level CVD DALYs were projected using autoregressive integrated moving average (ARIMA) models fitted to 2011--2021 GBD data. The population attributable fraction (PAF = 0.28%) was applied to projected DALY counts. State-level values are shown at each state's geographic centroid. The colour gradient ranges from light (lower burden) to dark (higher burden). Uttar Pradesh

(35,405), Maharashtra (25,670), and West Bengal (24,046) are projected to carry the largest attributable burden.

DALY = disability-adjusted life year; CVD = cardiovascular disease; HI = Heat Index; PAF = population attributable fraction; ARIMA = autoregressive integrated moving average.

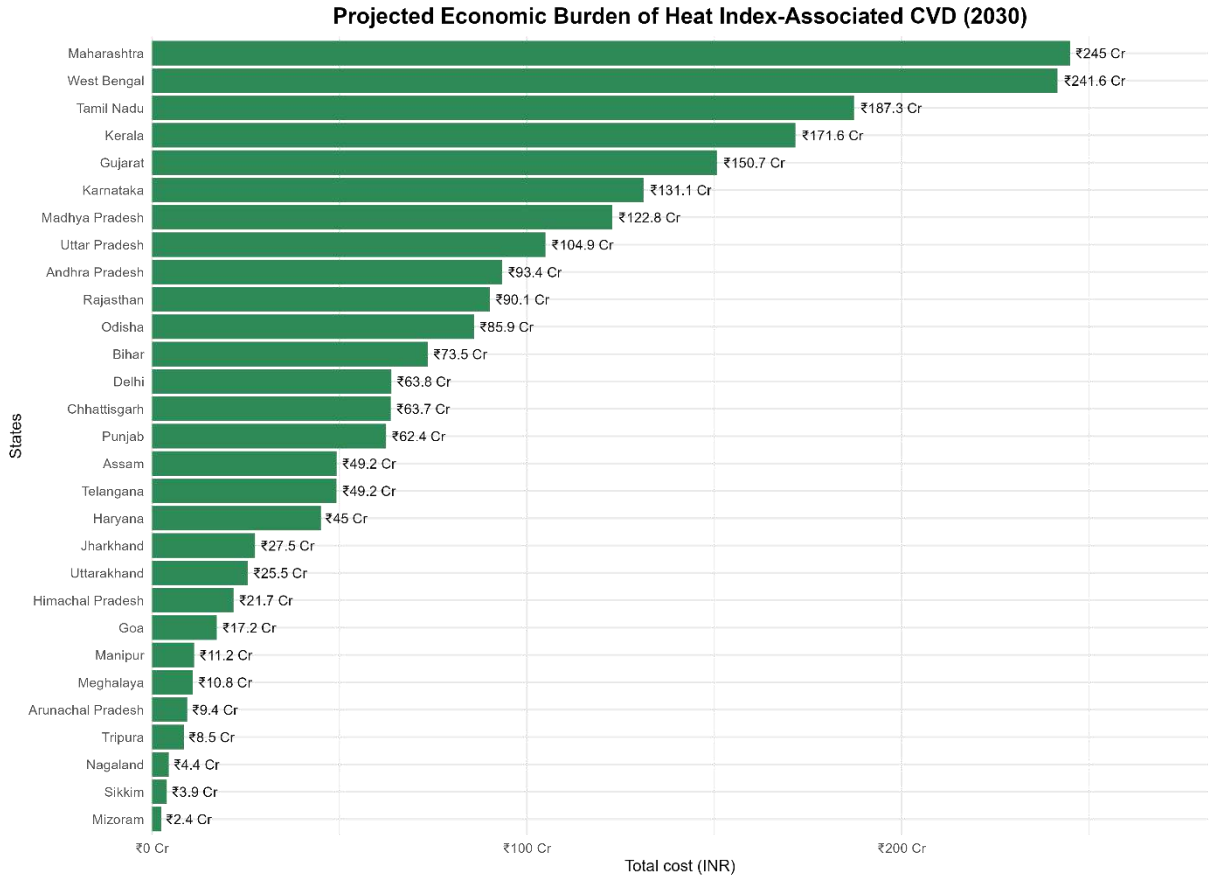


Figure 4.

Projected State-Wise Economic Burden of Heat Index-Attributable CVD, 2030

Note. Horizontal bar chart showing the projected total economic burden (in INR Crore) of cardiovascular disease (CVD) DALYs attributable to high Heat Index (HI) exposure for

each Indian state in 2030. Projected economic burden was computed as the product of ARIMA-forecasted attributable DALYs and cost per DALY projected at a 3% compound annual growth rate (CAGR) from 2021 baseline values. States are ordered by descending magnitude. Maharashtra is projected to have the highest economic burden, followed by West Bengal and Kerala. The projected national total is approximately INR 2,178 Crore (~USD 292 million).

DALY = disability-adjusted life year; CVD = cardiovascular disease; HI = Heat Index; ARIMA = autoregressive integrated moving average; CAGR = compound annual growth rate; INR = Indian Rupee; Cr = Crore (10 million); CpD = cost per DALY.

Table 1

Percent Change in CVD Burden per Unit Increase in Heat Index Metrics

Heat Index Metric	DALY	YLL	YLD
avg_975	1.62% (0.67%, 2.57%)	1.7% (0.7%, 2.7%)	-0.01% (-0.31%, 0.28%)
var_25	2.48% (-0.13%, 5.16%)	2.67% (-0.08%, 5.5%)	-0.74% (-1.51%, 0.05%)
var_975	-0.1% (-1.01%, 0.81%)	-0.12% (-1.08%, 0.84%)	0.32% (0.04%, 0.59%)

Note. Results from log-linear fixed-effects panel regression models estimating the percent change (95% CI) in cardiovascular disease (CVD) burden outcomes per one-unit increase in Heat Index (HI) metric, across 29 Indian states from 2011 to 2021. Three CVD burden outcomes were modelled: disability-adjusted life years (DALYs), years of life lost (YLL),

and years lived with disability (YLD). Three HI predictors were assessed: the 97.5th percentile of average HI (avg_975), the 2.5th percentile of HI variation (var_25), and the 97.5th percentile of HI variation (var_975). Each model included state and year fixed effects to control time-invariant confounders and common temporal trends.

CI = confidence interval; DALY = disability-adjusted life year; YLL = years of life lost; YLD = years lived with disability; HI = Heat Index; CVD = cardiovascular disease.

Supplementary Files

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- 20260519supplementarymaterial.docx