Exploring the impacts of humid-heatwave dynamics and population density on heat-exposure risk in India

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Abstract

In recent years, humid heatwaves have been shown to be the deadliest form of heat stress. This study examines trends in humid heatwaves, estimated via wet-bulb temperature (WBT), and their impact on heat-related deaths (HRDs) across India from 2001 to 2022 using ERA5 reanalysis data. A heatwave event in a given area was defined as a three-day stretch in which the daily WBT in that area exceeded the 90th percentile computed separately for each state, capturing both localised thresholds and prolonged exposure. While changes in HRDs correlate with changes in humid-hot spells, state-level analysis reveals substantial interannual variability and disproportionate impacts. We show that factors beyond heatwave frequency and magnitude, such as population density, play a crucial role in shaping the relationship between heat exposure and mortality. These findings emphasise the need for state-specific interventions, urban heat mitigation strategies, and long-term investments in resilience to protect vulnerable populations from escalating heatwave risks.

1. Introduction

Heatwaves are prolonged periods of extreme heat that pose growing risks to public health, infrastructure, economies, energy systems, and ecosystems, especially in densely populated India [10]. These events especially increase mortality, strain energy systems, and cause economic losses, disproportionately affecting vulnerable groups [5]. As the climate changes, understanding the corresponding changes in heatwave trends is crucial for effective adaptation and mitigation. While previous studies into heat-related mortality have primarily focused on dry-heat spells, recent research has shown that humid-heat spells pose an even greater threat , which could intensify with global warming. Relatively humid regions like India, home to one-sixth of the global population, could face heightened risks from heat exposure. This study aims to understand how the changing dynamics of humid heatwaves, specifically their frequency and intensity, shape their impact on mortality in India. Gaining this insight is crucial for developing effective mitigation and adaptation strategies to reduce heat-related risks as India’s climate challenges grow.

2. Data and Methodology

2.1. Data Sources

This study derives WBT from daily maximum temperature (t2m) and dewpoint temperature (d2m) data in the fifth generation of the global atmospheric reanalysis dataset (2001–2022) from the European Centre for Medium-range Weather Forecast (ERA5). These files were obtained in NetCDF format. A shape file[11] of Indian states' boundaries was converted to GeoJSON format. Population density estimates for India were obtained from the United Nations Data Portal Population Division. Additionally, we incorporated heat-stroke and related death data published by the Open Government Data Platform India to assess moist heat's relationship with mortality. By combining these climate, geographical, and population data streams, we analysed heat trends and their societal impacts across India at the state level.

2.2. Data Extraction Methods

First, temperature and dewpoint data (monthly, yearly) were read from the ERA5 NetCDF files using Xarray. Temperatures were converted from Kelvin to Celsius, and WBT was computed for each grid cell using the following formula:

WBT = t * arctan(0.151977 * (rh + 8.313659)**0.5) + arctan(t + rh) - arctan(rh - 1.676331) + 0.00391838 * rh**1.5 * arctan(0.023101 * rh) - 4.686035

Where:

WBT is the Wet Bulb Temperature (in degrees Celsius)

t is the temperature (in degrees Celsius)
rh is the relative humidity (a value between 0 and 100)
arctan is the arctangent function (inverse tangent).

Relative humidity (rh) is computed as:

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rh = 100 * (np.exp((17.625 * d) / (243.04 + d)) / np.exp((17.625 * t) / (243.04 + t)))
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where *d* is dew point temperature and *t* is air temperature, both in °C.

Several steps were then performed to aggregate the gridded WBT data into a time series at the state level, allowing for heatwave calculations. First, the gridded dataset was restructured into a table, with each row containing the WBT at a given time for a cell centred at a given longitude and latitude. Aggregation at the state level was performed by spatially joining the WBT data to the Indian state boundary GeoJSON data; this effectively groups the WBT observations by state. The average is then calculated. The data are regrouped to compute annual-mean WBT for analysis. Finally, the processed data is merged into a single dataset.
We define heatwaves as a three-day stretch in which an area's daily WBT exceeds the 90th percentile for that area. The frequency of these events quantifies heatwave occurrences, capturing both intensity and duration.

3. Results and Discussions

3.1. Long Term Trends in Heat-Related Deaths (HRDs)

Our analysis reveals that heat-related deaths generally trend upward in 2001-2022, highlighting the impact of the warming climate on the increasing vulnerability of populations to extreme heat events. The time series analysis indicates that HRDs have significantly increased over the past two decades, which correlates with rising global temperatures and more frequent heatwave occurrences.

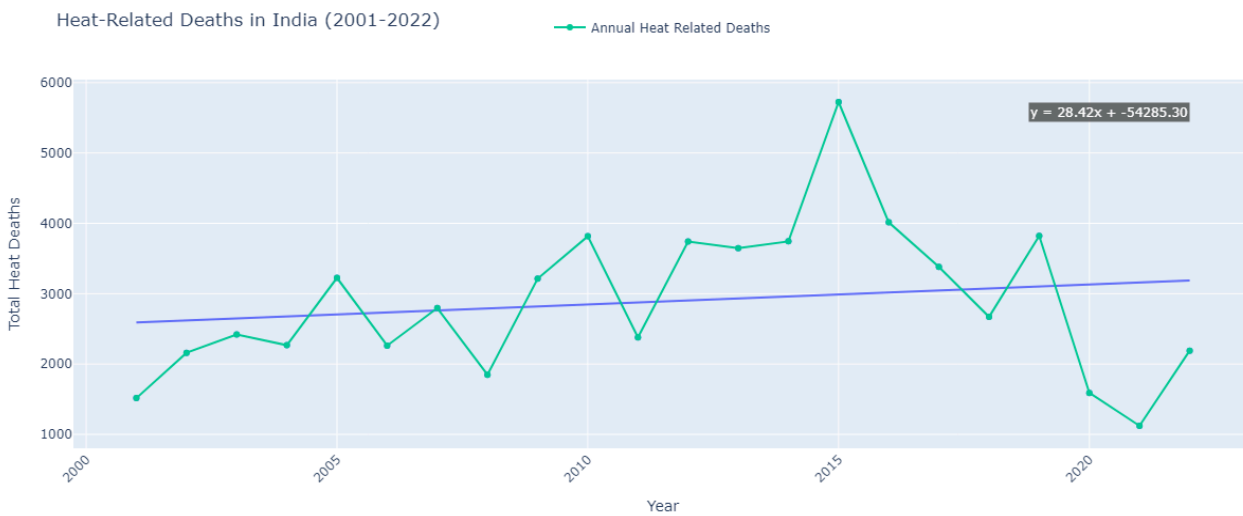

Figure 1: Heat-related deaths in India from 2001-2022. The green and blue lines show the annual number of heat-related deaths and the trend line, respectively.

3.2. Heatwave Characteristics and Their Correlation with HRDs

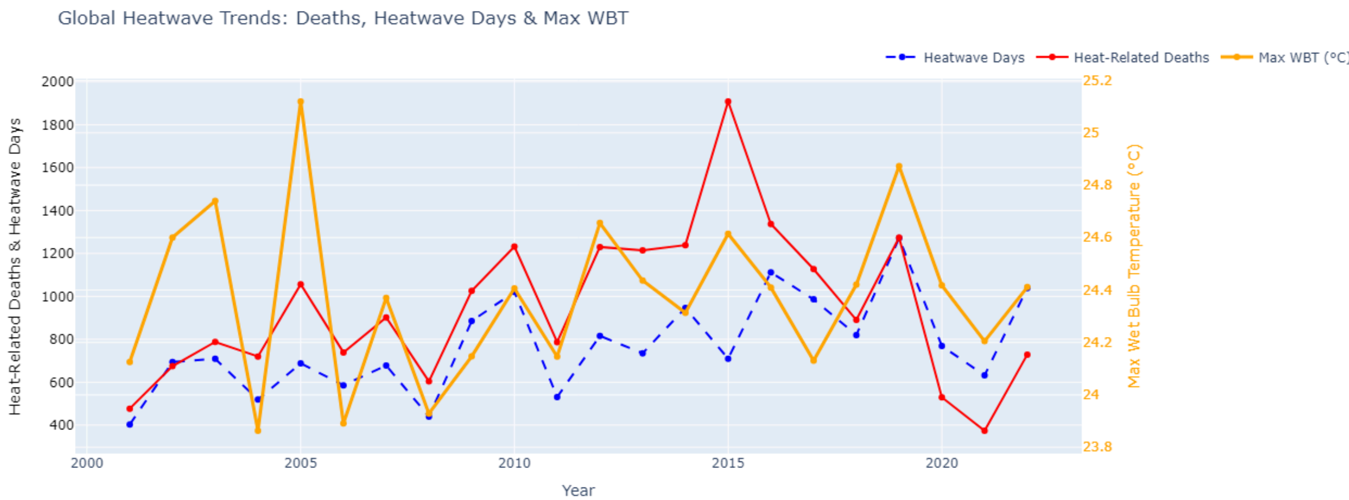

Figure 2: Global heatwave days, heat-related deaths and heatwave magnitude (Max WBT), 2001-2022

HRDs are influenced by both heatwave frequency (extreme heat days per year) and magnitude (intensity and duration). Our analysis shows a moderate correlation, suggesting prolonged heat exposure increases fatalities. However, non-linearity within this trend could indicate other mediating factors, such as humidity, urban heat islands (UHIs), and socio-economic vulnerabilities, also influence mortality. While frequent heatwaves increase cumulative exposure, extreme-intensity events can be particularly deadly, even if rare. Understanding this dual impact is crucial for enhancing mitigation strategies and early warning systems.

3.3. Role of Changing Population Density in Heat-Related Deaths

Heat-related deaths (HRDs) correlate with heatwave frequency and magnitude but not strictly linearly, suggesting other factors like population density (PD) play a role. Higher PD increases the risk of heat-related deaths by amplifying exposure to extreme heat conditions. Urban areas with high PD amplify heat via the UHI effect, in which concrete infrastructure absorbs and retains heat, boosting ambient temperatures. Data shows states with higher PD report more HRDs, especially in metro regions, underscoring the need for urban cooling strategies like increasing vegetation cover and reflective surfaces. The weak linear correlation between HRDs and heatwaves suggests confounding factors that modulate the relationship between them.

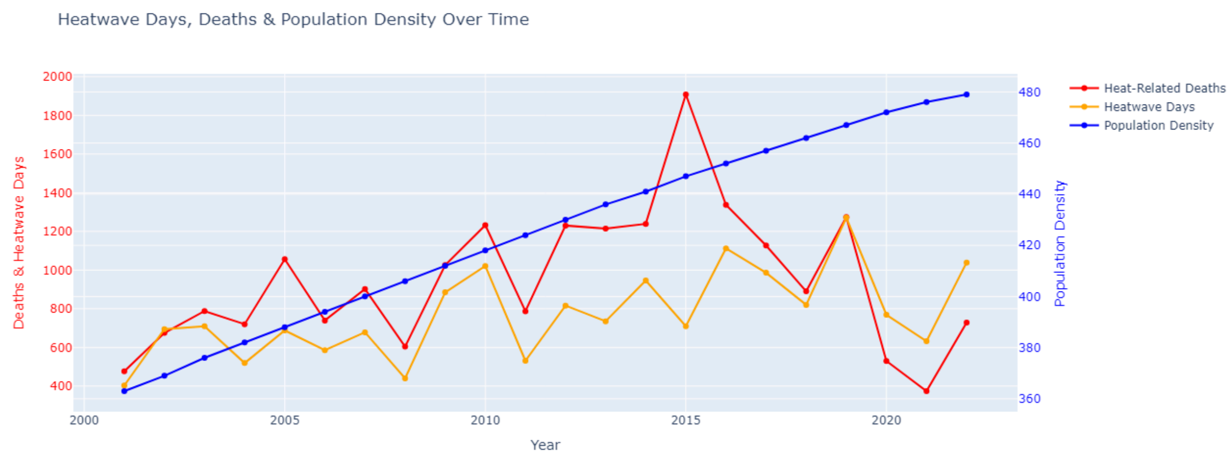

Figure 3: Heatwave days, deaths & population density over time

3.4. Population Density and the 2015 Anomaly

From 2001 to 2022, India experienced a consistent upward trend in population density, as shown by the blue line, while heat-related deaths (red line) and heatwave days (orange line) exhibited significant interannual variability. Although population density increased steadily, heat-related deaths and heatwave days fluctuated, peaking around 2015 before showing some signs of decline, suggesting potential mitigation efforts or adaptation strategies may have had some impact.

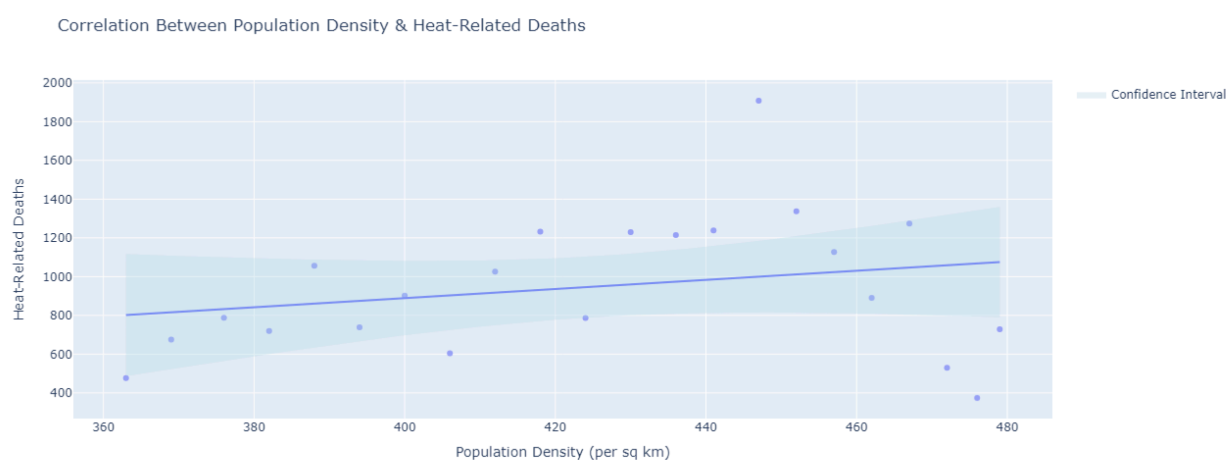

Figure 4: Correlation between population density & heat related deaths

Figure 4 illustrates the correlation between population density and heat-related deaths, where each point represents a year's data. The plot includes a trendline with a confidence interval, visually representing the uncertainty in the trend. The upward sloping trendline suggests there is a positive correlation between population density and heat-related deaths, though the wide confidence interval suggests a weak relationship**.**

State-Specific Trends in Heatwave Days and Heat-Related Deaths: A Comparative Analysis (2005, 2015, 2019)

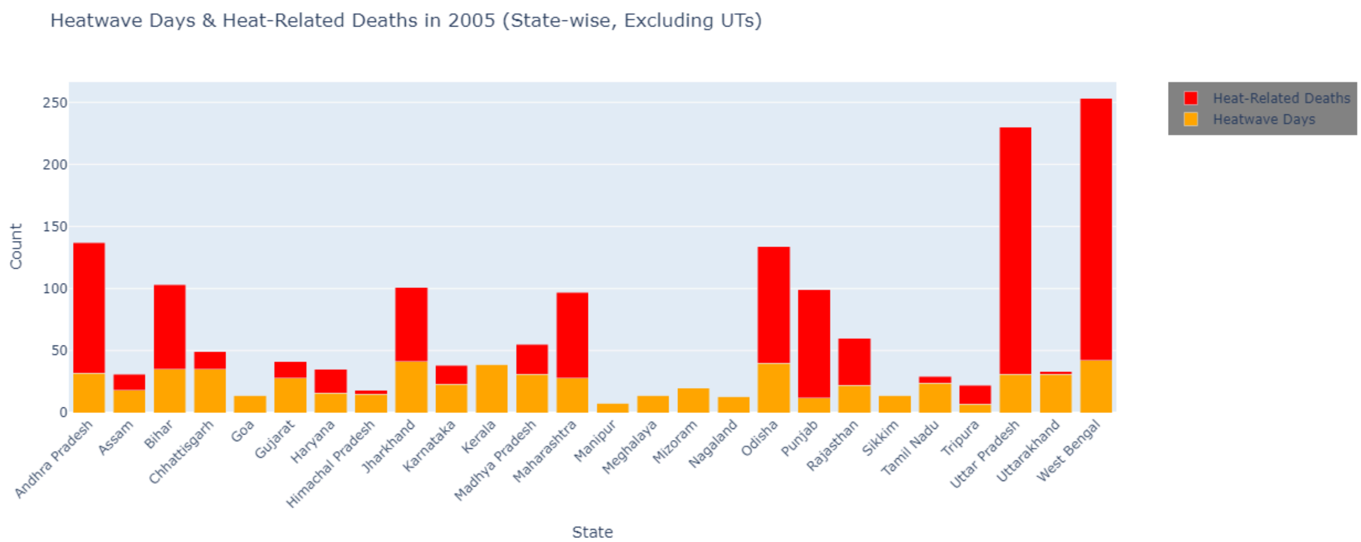

Figure 5: State-wise heatwave days & heat-related deaths in 2005

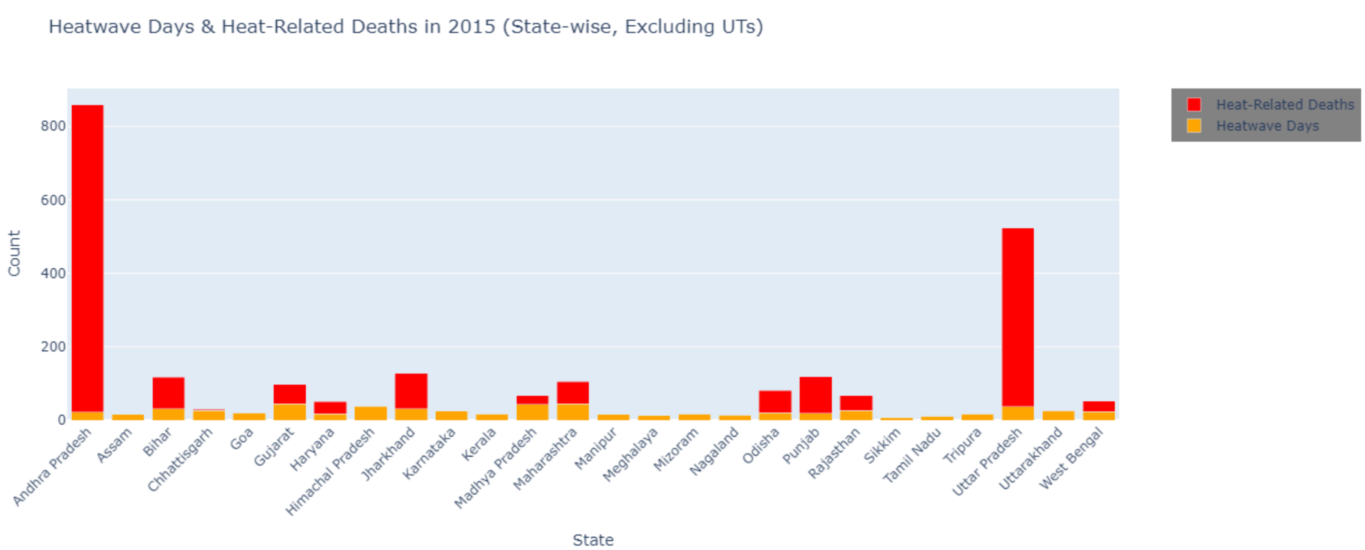

Figure 6: State-wise heatwave days & heat-related deaths in 2015

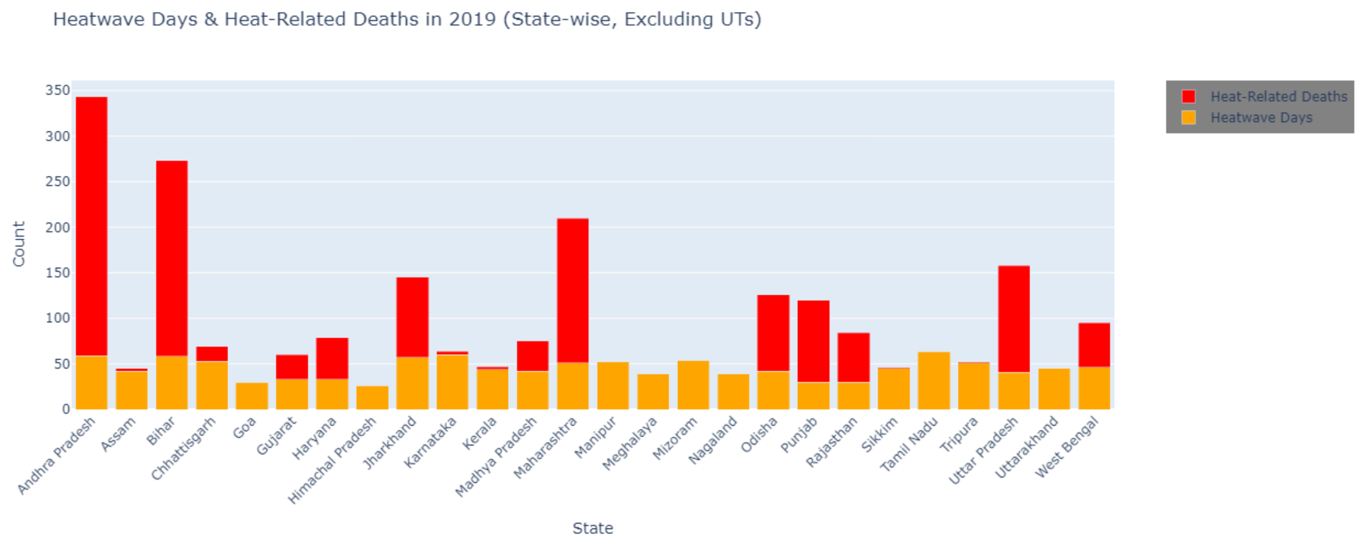

Figure 7: State-wise heatwave days & heat-related deaths in 2019

Analysing the state-level trends in heatwave days and heat-related deaths across 2005, 2015, and 2019 reveals several critical observations and state-specific vulnerabilities.

In 2005, West Bengal reported the highest heat-related deaths despite fewer heatwave days. Its high-ranking population density (2nd in India, per the 2011 census) or other socioeconomic factors (such as cooling access) may have made West Bengal more vulnerable, magnifying the heat's deadliness. Andhra Pradesh, Uttar Pradesh, and Odisha also saw significant fatalities.

In 2015, heat-related deaths in Andhra Pradesh rose sharply, far exceeding heatwave days and other states, indicating extreme vulnerability and possible lack of preparedness. Uttar Pradesh and Telangana also recorded significant fatalities, reflecting the widespread impact.

In 2019, heat-related deaths spread across more states. While Andhra Pradesh remained a concern, heatwave days and fatalities also grew dramatically in Bihar, Maharashtra, Punjab, and Uttar Pradesh relative to 2015. indicating that the impact of heatwaves is becoming more widespread, even though fatalities nationwide fell in that span.

Insights and Implications

- Disproportionate impact: In many instances, the number of heat-related deaths is not directly proportional to the number of heatwave days. This highlights the potential importance of other factors. These include::
    - Socioeconomic stressors: Poverty, healthcare access, cooling-resource availability

    - Population density: Denser areas may experience higher heat-related mortality due to the UHI effect and increased strain on resources.

    - Public health interventions: States with early-warning systems, heat-action plans, and public-awareness campaigns can better manage heatwaves' health risks.

- Regional vulnerabilities: Certain states, like Uttar Pradesh, appear to be consistently more vulnerable to heat-related mortality, based on their death tolls. Notably, Andhra Pradesh experienced an unprecedented surge in HRDs in 2015, exceeding all other states, suggesting that location-specific factors beyond heatwave frequency and magnitude influence heat-related mortality. This highlights the need for targeted interventions and adaptation strategies in these regions.

- Increasing geographic spread: The data suggest that heatwaves' impacts have been spreading geographically, with more states experiencing significant heat-related deaths in 2019 compared to 2005.

4. Conclusions and Future Work

4.1. Conclusions

This study of heatwave days and heat-related deaths across Indian states reveals a complex and evolving picture of heatwave impacts. While certain states, such as Andhra Pradesh and Uttar Pradesh, consistently exhibit higher vulnerability, the specific patterns and severity vary significantly from year to year. The 2015 surge in HRDs isolated to Andhra Pradesh highlights the importance of factors beyond heatwaves, particularly population density, socioeconomic conditions, and preparedness measures. Decreases in HRDs since 2015 suggest that adaptation strategies may be moderating heat-related mortality, warranting continued investment and refinement. Future research should focus on identifying and addressing each state's specific vulnerabilities, evaluating the effectiveness of current adaptation approaches, and devising strategies tailored to a steadily urbanising India. Ultimately, a multifaceted approach, combining targeted interventions with broad-based strategies, is essential to safeguarding populations from the increasing risks of extreme heat.

4.2. Future Work

While this study provides a strong foundation for understanding heatwave trends and mortality patterns, several areas require further research:

1. State-specific adaptation measures: Future research should analyse the effectiveness of state-wise policies and adaptation strategies in reducing heat-related deaths.

2. Microclimate analysis: Incorporating remote-sensing and ground-level monitoring data to examine local temperature variations, UHIs, and their impact on mortality.
3. Long-term predictive modeling: Developing machine learning models to predict future heatwave events and their health impacts.
4. Vulnerability assessment: A deeper investigation into socioeconomic factors such as income levels, occupation types, and healthcare access in high-risk regions.
5. Assessment of risk-management strategies: Evaluating the effectiveness of cooling shelters, afforestation, and land use in managing heat risks.

By expanding on these aspects, future studies can contribute to a more comprehensive, data-driven approach to heatwave preparedness and resilience in India and other vulnerable regions.

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