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How Extreme Heat is Impacting India

Assessing District-level Heat Risk

Shravan Prabhu, Keerthana Anthikat Suresh, Srishti Mandal, Divyanshu Sharma, and Vishwas Chitale

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This independent academic study covers 734 districts across all Indian states and is based entirely on open-access data from publicly available sources. Government stakeholder consultations and state government data were not part of the study process. The state-level findings will be validated through further ground-truthing in due course.

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How Extreme Heat is Impacting India

Assessing District-level Heat Risk

Shravan Prabhu, Keerthana Anthikat Suresh, Srishti Mandal, Divyanshu Sharma, and Vishwas Chitale

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More than 23 states, home to nearly one crore Indians, are prone to frequent heatwaves in India (IMD 2023).

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The Council on Energy, Environment and Water (CEEW) is one of Asia's leading not-for-profit policy research institutions and among the world's top climate think tanks. The Council uses **data, integrated analysis, and strategic outreach to explain — and change — the use, reuse, and misuse of resources**. The Council addresses pressing global challenges through an integrated and internationally focused approach. It prides itself on the independence of its high-quality research, develops partnerships with public and private institutions, and engages with the wider public. CEEW is a strategic/ knowledge partner to 11 ministries for India's G20 presidency.

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The Council's major contributions include: informing India's net-zero goals; work for the PMO on accelerated targets for renewables, power sector reforms, environmental clearances, and *Swachh Bharat*; pathbreaking work for India's G20 presidency, the Paris Agreement, the HFC deal, the aviation emissions agreement, and international climate technology cooperation; the first independent evaluation of the *National Solar Mission*; India's first report on global governance submitted to the National Security Advisor; support to the *National Green Hydrogen and Green Steel Missions*; the 584-page *National Water Resources Framework Study* for India's 12th Five Year Plan; irrigation reform for Bihar; the birth of the Clean Energy Access Network; the concept and strategy for the International Solar Alliance (ISA); the Common Risk Mitigation Mechanism (CRMM); India's largest multidimensional energy access survey (ACCESS); critical minerals for Make in India; India's climate geoengineering governance; analysing energy transition in emerging economies, including Indonesia, South Africa, Sri Lanka, and Vietnam. CEEW published Jobs, Growth and Sustainability: A New Social Contract for India's Recovery, the first economic recovery report by a think tank during the COVID-19 pandemic.

The Council's current initiatives include: state-level modelling for energy and climate policies; planning for the consumer-centric smart metering transition and wholesale power market reforms; modelling carbon markets; piloting business models for solar rooftop adoption; projecting fleet electrification and developing low-emission zones across cities; assessing green jobs potential at the state level, designing a circular economy for solar supply chains and wastewater; assessing carbon pricing mechanisms and India's carbon capture, usage, and storage potential; developing a first-of-its-kind Climate Risk Atlas for India; designing sustainable cooling solutions; developing state-specific dairy sector roadmaps; supporting India's electric vehicle and battery ambitions; and enhancing global action for clean air via a global commission called 'Our Common Air'.

The Council has a footprint in over 20 Indian states, working extensively with 15 state governments and grassroots NGOs. Some of these engagements include supporting power sector reforms in Uttar Pradesh, Rajasthan, and Haryana; informing energy policy in Rajasthan, Jharkhand, and Uttarakhand; driving low-carbon transitions in Bihar, Maharashtra, and Tamil Nadu; promoting sustainable livelihoods in Odisha, Bihar, and Uttar Pradesh; advancing industrial sustainability in Tamil Nadu, Uttar Pradesh, and Gujarat; evaluating community-based natural farming in Andhra Pradesh; supporting groundwater management and e-auto adoption; and examining crop residue burning in Punjab.

By 2050, almost every child in the world—nearly 2.2 billion children—will be exposed to frequent heat waves (UNICEF 2024).

Image: iStock

Contents

India could lose the equivalent of 35 million full-time jobs and experience a 4.5% reduction in GDP by 2030 due to heat stress (ILO 2019).

Image: iStock

Executive summary

Extreme heat broke all records in 2024, which was recognised globally as the hottest year since records began. **Asia**, which accounted for **45 per cent of global heat-related deaths between 2000 and 2019**, and **India**, where **over a billion people face heatwaves annually**, remain among the most affected regions (WHO 2024; IMD 2023). In 2024, India experienced its longest recorded heatwave since 2010. Many states experienced daytime temperatures of over 40°C for an entire month, leading to more than 44,000 cases of heatstroke (Patel et al. 2024). By April 2025, more than 10 states had already experienced severe heatwaves.

Extreme heat is already having a multifaceted impact on day-to-day life, straining public health systems, pushing power demand to record highs, damaging crops, depleting water resources, and reducing the productivity of humans, livestock, and agriculture. Due to heat stress, India could lose the equivalent of **35 million full-time jobs and experience a 4.5 per cent reduction in GDP by 2030** (Kjellström et al. 2019).

At this juncture, India must rapidly scale up its heat resilience. To achieve this, a granular, data-driven understanding of the heat risk faced by every district in the country is one of the first and most crucial step.

Figure ES1 Extreme heat disproportionately affects vulnerable groups

By age/health
- Elderly
- Young children
- Pregnant women
- Individuals with chronic conditions

By social context
- Marginalised communities*
- Slum dwellers

By occupation
- Gig workers / Delivery riders
- Police personnel
- Agricultural labourers
- Construction workers

Source: Authors' compilation

* Note: 'Marginalised communities' refers to Scheduled Caste (SC) and Scheduled Tribe (ST) groups, based on data aggregated at the district level.

Why does India need a composite heat risk assessment to advance heat resilience?

Heat is often called an invisible disaster because it does not leave behind physical destruction, making it harder to measure its impact.

Heat risk depends on three interlinked factors: i) the intensity of heat and compounding factors such as rising relative humidity; ii) the number of people exposed and their geographic distribution; and iii) the vulnerability of those exposed. **Extreme heat does not affect everyone equally**. However, **most existing studies address only isolated aspects of the problem—**by mapping temperature trends, estimating productivity losses, or analysing socio-economic vulnerabilities—resulting in a fragmented understanding of heat risk.

Second, India's primary strategy for tackling extreme heat is through heat action plans (HAPs). These plans have reduced the occurrence of heat-related illnesses and mortalities in the last decade; however, they need further strengthening, since **95 per cent of HAPs lack a detailed assessment of heat risks and vulnerabilities** (Pillai and Dalal 2023). This gap makes it challenging for authorities to pinpoint and prioritise high-risk areas and allocate financial resources effectively. This is particularly relevant as heatwaves, since 2024, are now eligible for financing under state disaster mitigation funds (SDMFs) (Ministry of Home Affairs 2024). Comprehensive risk assessment is a prerequisite to availing such funding and is key to implementing effective solutions.

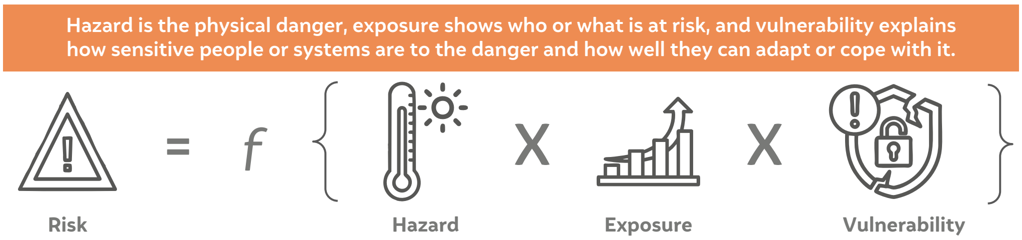
Mapping heat risk across India's districts

In this study, we have developed a heat risk index (HRI) for 734 districts in India to assess heat risk at the district scale. The index is based on the Intergovernmental Panel on Climate Change (IPCC) AR5 framework, which **defines "risk as a combination of hazard, exposure, and vulnerability"** (IPCC 2014).

In our HRI, we mapped long-term heat trends (1982–2022) using the Indian Monsoon Data Analysis and Assimilation (IMDAA)—a high-resolution climate dataset that breaks down India's area into 12-km grids. Along with this climatological analysis, we used satellite imagery to map changes in 35 critical indicators (Table 3 to 5) pertaining to land use and land cover dynamics, human population and building density, distribution of water bodies, and green cover. We combined this with data on socio-economic and health vulnerabilities from the NFHS 2019–21 and Census 2011, which are the latest available datasets. Our analysis also integrated **nighttime temperatures and relative humidity** for a more comprehensive understanding of heat hazard beyond daytime temperatures.

To select the indicators and assign weights to them for the HRI, we consulted experts from research institutes and think tanks through a semi-quantitative method known as the analytical hierarchy process.

Figure ES2 **The IPCC AR5 risk assessment framework was used to develop a heat risk index based on 35 indicators**



Source: Authors' compilation

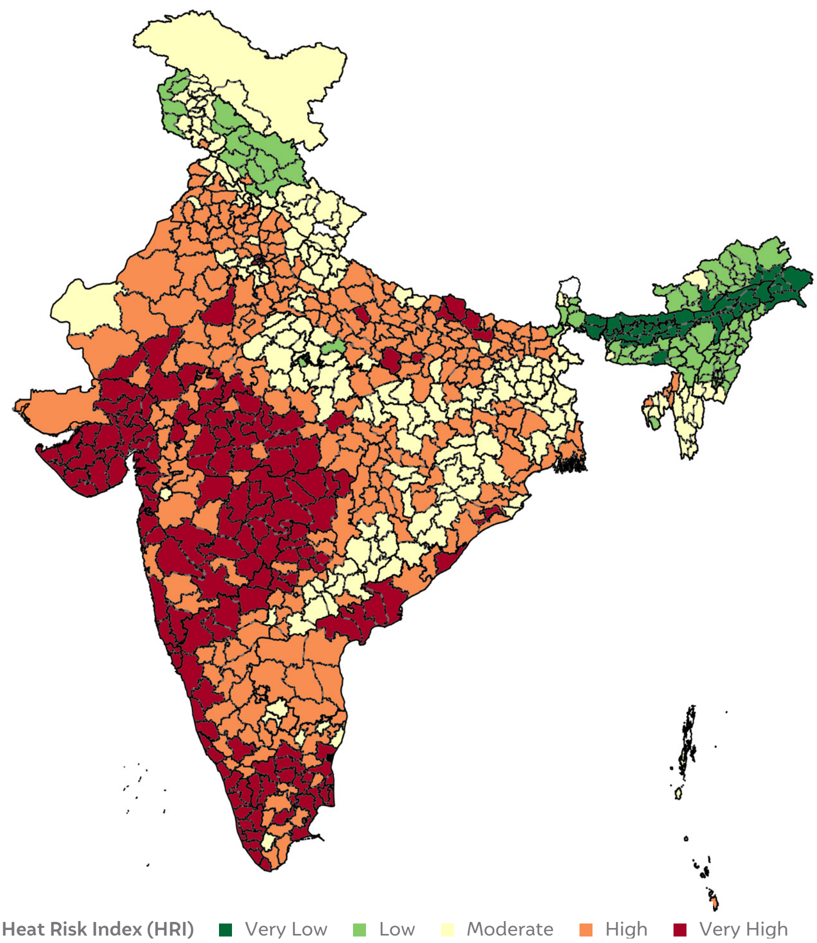
Indian cities are warming twice as fast as the rest of the country (Sethi and Vinoj 2024). However, we chose districts as our unit for analysis for two reasons: i) disaster risk governance and institutional responsibilities in India are anchored at the district level, making it a functionally appropriate scale for planning and implementation; and ii) consistent and comprehensive socio-economic and demographic datasets—particularly from Census 2011 and NFHS 2019–21—are available only at the district scale. Accordingly, we assessed heat risk in 734 districts in India based on the boundaries defined by the Survey of India's geographic information system shapefile as of March 2025 (SOI 2022).

Key findings

About 57 per cent of Indian districts, home to 76 per cent of India's total population, are currently at high to very high heat risk. We found that 417 out of 734 Indian districts fell in the high and very high risk categories (151 under high risk and 266 under very high risk), as seen in Figure ES3. Moreover, 201 districts fell in the moderate category, and 116 fell in either the low or very low categories. This does not indicate that these districts are free of heat risk, but that it is relatively lesser than that of other districts.

Aggregating these risks at the state level, we found that the ten states and UTs with the highest heat risk are Delhi, Maharashtra, Goa, Kerala, Gujarat, Rajasthan, Tamil Nadu, Andhra Pradesh, Madhya Pradesh, and Uttar Pradesh.

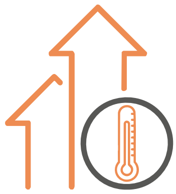
Figure ES3 More than 57% of districts are at high to very high heat risk in India



Source: Authors' analysis

Decoding this further, we have identified key drivers that explain this risk and the factors contributing to high and very high risk levels.

1. **The number of very hot days is increasing in India, but concerningly, the number of very warm nights is increasing even more, creating health risks.**



A percentile ranks temperatures against historical data; the 95^{th} percentile means 95% of past temperatures were below that value

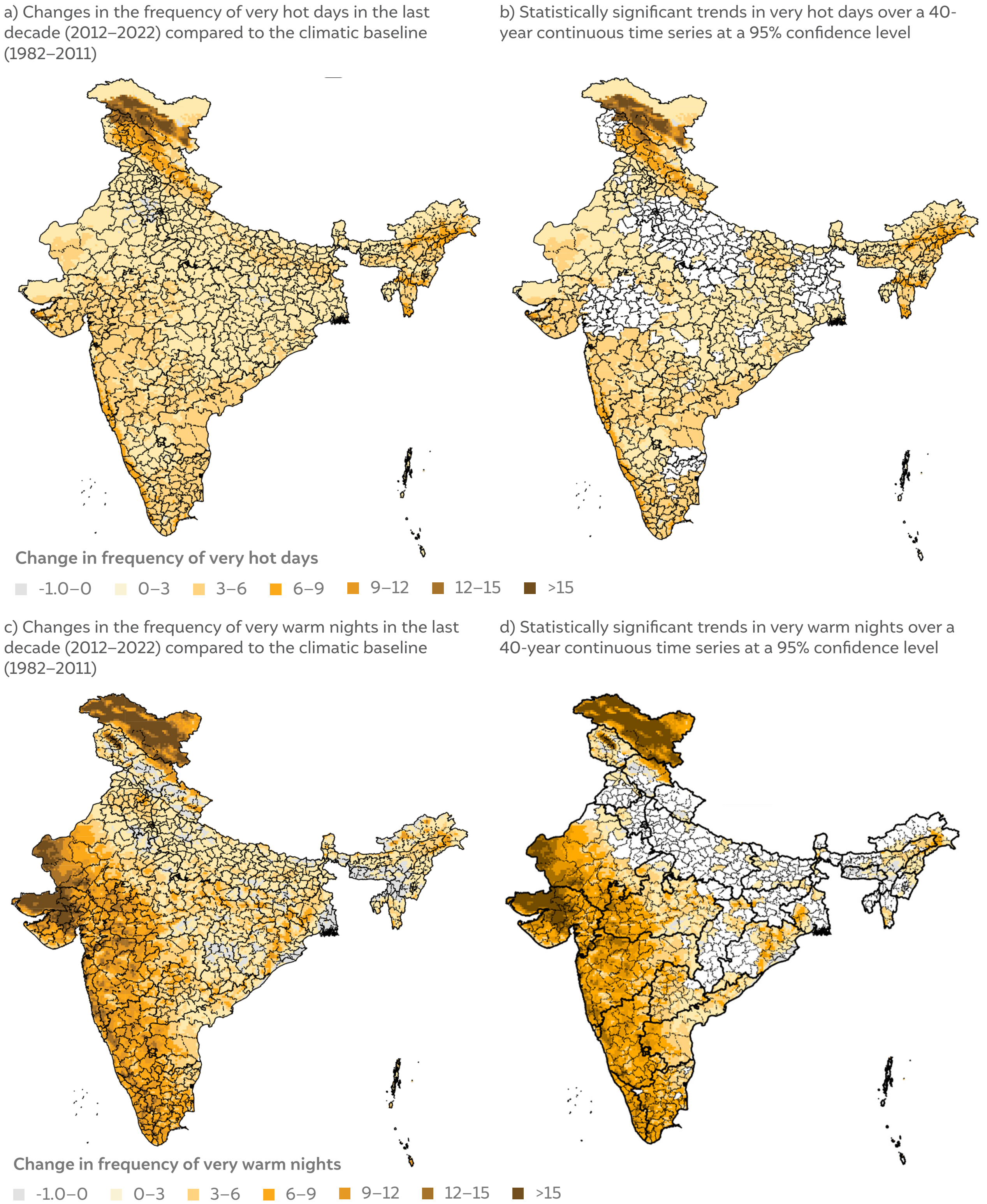
Over the last 40 years (1981–2022), heat extremes in India have increased linearly. This led to landmark heatwaves in 2013, 2016, 2019, 2022, and 2024. However, in the last decade, the number of very warm nights has been rising faster than that of very hot days. These nights and days are defined as periods when minimum and maximum temperatures rise above the 95th percentile threshold, i.e., what was normal for 95 per cent of the time in the past. Global weather patterns like El Niño and La Niña have also significantly affected the extent to which temperatures rise during the day and night (see Figure 3).

Warmer nights prevent the human body from cooling down after intense daytime heat. This significantly increases health risks such as heat strokes and worsens non-communicable diseases such as diabetes and hypertension. This is pertinent, especially for vulnerable populations such as children, the elderly, pregnant women, those from marginalised backgrounds, and those with existing chronic health conditions.

Our district-level analysis of the heat risk over the last decade (2012–2022) reveals shifting heat patterns across the 734 Indian districts as compared to the baseline of 1982–2011.

- **Over the last decade, nearly 70 per cent of districts experienced an additional five very warm nights per summer (March to June). In comparison, only ~28 per cent of districts experienced five or more additional very hot days.**
- The rise in very warm nights is most noticeable in districts with a large population (over 10 lakh), which are often home to tier I and II cities. In the last decade, **Mumbai saw 15 additional very warm nights per summer, Bengaluru (11), Bhopal and Jaipur (7 each), Delhi (6), and Chennai (4)**. This increase can be attributed to the urban heat island effect, where cities trap heat during the day and release it at night, thus increasing nighttime temperatures. With nearly 50 per cent of India's population expected to live in urban areas by 2050, this poses a serious threat to the population (UN-DESA 2018).
- We found that even in the traditionally cooler Himalayan regions—where heat thresholds are lower than in the plains and coasts—both very hot days and very warm nights have increased. For example, in the union territories of Jammu & Kashmir and Ladakh, the number of very hot days and very warm nights has risen by over 15 days and nights each summer. This could severely impact fragile mountain ecosystems.

Figure ES4 **During 2012–2022, ~70% of Indian districts experienced five more very warm nights per summer than the climate baseline of 1982–2011**



Source: Authors' analysis

2. **In the last decade, the Indo-Gangetic Plain experienced the highest summer relative humidity increase, exacerbating heat stress.**

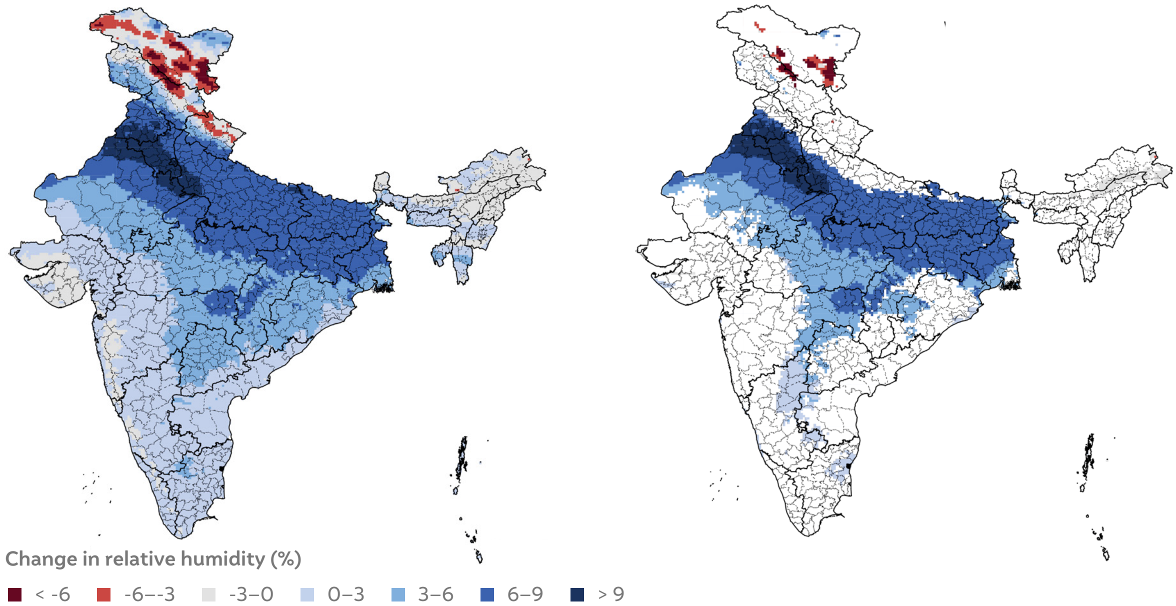
Increasing relative humidity is especially pronounced in North India, particularly across the agriculturally important Indo-Gangetic Plain (see ES Figure 5), where farm workers spend long hours outdoors. Cities like Delhi, Chandigarh, Jaipur, and Lucknow are also experiencing a 6 to 9 per cent rise in relative humidity. While coastal areas typically have 60–70 per cent relative humidity, North India used to have around 30–40 per cent during the baseline period. Over the past decade, this has increased to 40–50 per cent. Although humidity is highest during early mornings, when combined with high temperature, high humidity significantly worsens heat stress on the human body, especially during the peak summer months of May and June.

When the body temperature exceeds 37°C (or 100°F), sweating helps cool it down; however, high humidity slows this process, making it harder for the body to release heat (Baldwin et al. 2023). This can increase the occurrence of several heat-related illnesses at a faster rate.

Figure ES5 Between 2012–22, during the summer months (March to June), relative humidity rose by up to 10% in North India

a) Changes in summer relative humidity (%) in the last decade (2012–2022) compared to the climatic baseline (1982–2011)

b) Statistically significant trends in summer relative humidity (%) over a 40-year continuous time series at a 95% confidence level



Source: Authors' analysis

3. **Heat risk is caused by more than just temperature and relative humidity increases—dense buildings and existing socio-economic and health vulnerabilities make it worse.**

We found that the following factors exacerbated the risk of very hot days, very warm nights, and relative humidity.

- Districts with high population density like **Mumbai, Delhi, and many parts of the Indo-Gangetic Plain face the highest exposure to extreme heat.**
- Between 2005 and 2023, built-up areas have expanded rapidly in almost every Indian district, especially in growing tier II and III cities such as Pune, Thoothukudi, Kolhapur, Mysuru, Kozhikode, Ajmer, Gurugram, and Guwahati. **Concretised and built-up surfaces in cities trap heat during the day and release it at night, making nights hotter.**
- Districts in **Andhra Pradesh, Maharashtra, Haryana, Punjab, Chhattisgarh, Bihar, and Uttar Pradesh are highly vulnerable to extreme heat.** This is due to the combined impact of high temperatures as well as socio-economic and health vulnerabilities, including the high prevalence of non-communicable diseases (anaemia, diabetes, hypertension), and the significant share of elderly persons (60+ years) and young children (under 5 years years) in the population, all of whom are more vulnerable to extreme heat.
- In contrast, **districts with increased heat extremes but lower vulnerability, such as in Odisha, had higher green cover and better blue infrastructure**. These factors enhance adaptive capacity, helping communities cope more effectively with extreme heat.

Over 70% of Indian districts now face 5+ extra very warm nights yearly, with 28% seeing a rise in very hot days

D. Bridging the heat resilience gap: Utility of the study and recommendations

Our study provides actionable insights for heat risk—informed decision-making across various sectors, including water resources, agriculture, public health, and power. More importantly, we aim to support disaster management authorities at the state, city, and district levels in strengthening HAPs through a data-driven approach. By doing so, we aim to enable more efficient allocation of financial resources based on district-level heat risk factors.

Based on the findings from our assessment, we offer the following overarching recommendations.

1. **States, districts, and cities should move beyond a narrow focus on daytime temperatures while planning for heat risk and incorporate additional dimensions of warm nights, humidity, demographic patterns, and health vulnerabilities.**

Our review of publicly available HAPs from 15 states (as of January 2025) revealed that only Bihar and Andhra Pradesh have conducted any heat vulnerability mapping. To address this gap, **we have developed simplified, ready-to-use handbooks for every state and UT (Annexure 1). These handbooks present district-level heat risk maps, outline key risk drivers, and offer a clear basis for improved decision-making and resource targeting.**

Moreover, since last few years, the India Meteorological Department (IMD) has incorporated additional risk parameters such as percentile-based nighttime and day time temperature exceedance levels, hot and humid weather warnings into its multi-hazard meteorological forecasts. We recommend states, districts and cities should integrate these enhanced forecasts—in addition to the official heatwave criteria forecasts—into early warning systems and HAPs, to anticipate multi-sectoral impacts such as outbreaks of heat-related illnesses, power demand and ensure last-mile delivery of heat advisories and support services to vulnerable populations.

2. **Utilise the state disaster mitigation fund (SDMF) for heat risk reduction**

In 2024, the Ministry of Home Affairs (MHA) included heatwaves as nationally eligible disaster for receiving project-based funding under the SDMF (Ministry of Home Affairs 2024). SDMF has a national allocation of INR 32,031 crore for FY 2021–26 (15th FC 2020). This fund can be channelled towards heat risk reduction solutions including structural infrastructure (such as cooling shelters) as well as fund non-structural interventions (such as early warning systems and nature-based solutions). As per SDMF guidelines, comprehensive assessments of hazard, vulnerability, and risk is one of the most important step to identify at-risk areas and implement any solution. We urge SDMAs and state emergency operations centres to utilise our district-level analysis (Annexure 1) to identify high-risk geographies and prepare targeted proposals that are aligned with the framework issued by the National Disaster Management Authority (NDMA).

3. **States where more than 50% of districts experience high or very high heat risk should formally notify heatwaves as a state-specific disaster**

Doing so would unlock an additional 10 per cent of funds from the SDRF, thereby increasing the effective pool of disaster management funds to 30 per cent. These response funds can be channelled towards i) ex-gratia payments for heat related fatalities; ii) compensation for agricultural and livestock losses; and iii) capacity-building efforts for frontline workers. Many states such as Maharashtra, Tamil Nadu, Andhra Pradesh, Telangana and Madhya Pradesh have already formally notified heatwaves as a state-specific disaster, and other states with high risk should follow suit to bolster their fiscal capacity to enhance response mechanisms to extreme heat events.

4. **Shift from heat-related economic loss absorption to risk-sharing through insurance mechanisms**

Our spatial analysis of heat risk patterns reveals significant regional coherence within and across states. This presents an opportunity to transition from reactive expenditure to pre-arranged risk-sharing instruments such as parametric heat insurance. Parametric insurance is based on pre-defined temperature thresholds and can enable rapid disbursement of payouts following extreme heat events. Pilot initiatives already exist: Nagaland SDMA successfully accessed funds through a rainfall-based parametric trigger (Mixides 2025), and members of the Self-Employed Women's Association in Ahmedabad availed of coverage linked to heat-specific parameters (Dickie, Jessop, and Patel 2023). Building on this model, we recommend developing regional parametric insurance mechanisms to enhance financial resilience and ensure timely compensation for heat-induced losses, particularly focusing on the livelihood losses for the outdoor workers.

5. **The Centre should establish a national repository of heat action plans**

During the course of this study, we found it challenging to evaluate the institutional adaptive capacity of districts due to the absence of HAPs in the public domain. To address this, we recommend creating an open-access, centralised, national-level HAP repository. This could be hosted by the NDMA and updated by the respective SDMAs. A national repository can help enhance transparency, facilitate cross-learning among states and districts, aid in monitoring implementation, and help identify gaps in the design and execution of HAPs.

1. Introduction

Image: iStock

The world is nearing the 1.5°C global warming threshold faster than anticipated, with 2024 being the hottest year on record globally and in India (WMO 2025; IMD 2025). This accelerated climate change disproportionately impacts developing nations such as India, increasing risks from extreme weather events. In Asia, which accounted for nearly 45 per cent of global heat-related deaths between 2000 and 2019, extreme heat-induced health impacts are a significant climate risk (WHO 2024).

India's annual average temperature has increased by 0.15°C per decade between 1951 and 2016, (Krishnan et al. 2020). This has led to a non-linear increase in the impacts of extreme heat, such as the deaths of over 24,000 people due to heat from 1992 to 2015, despite the challenges in attributing heat deaths (NDMA n.d.). Globally, heatwaves remain the deadliest natural hazard, having claimed around 4,89,000 lives annually between 2000 and 2019 (UN 2024).

Figure 1 Impact of extreme heat globally and in India

489,000 annual deaths from heatwaves globally per year[1]	**24,223** heat related deaths in India from 1992 to 2015[2]
Heat-related mortality for people >**65 years of age increased by approximately 85%** between 2000–2004 and 2017–2021[1]	By 2050 almost every child in the world — nearly **2.2 billion children** — will be exposed to frequent heat waves[3]
21% loss in global agricultural production due to heat and drought[4]	India could lose the equivalent of **35 million full-time jobs** by 2030 due to heat stress[5]
Periods of extreme heat cost the global economy about **USD 16 trillion** dollars between 1992 and 2013[6]	**4.5% of India's GDP could be at risk** by 2030 owing to lost labour hours from extreme heat and humidity conditions[7]

Source: Authors' compilation

Note: 1) United Nations. Secretary-General's Press Conference on Extreme Heat. July 25, 2024.

2) National Disaster Management Authority (NDMA). Beating the Heat: How India Successfully Reduced Mortality due to Heat Waves. New Delhi: National Disaster Management Authority, Ministry of Home Affairs, Government of India, n.d.

3) United Nations Children's Fund (UNICEF). The Coldest Year of the Rest of Their Lives: Protecting Children from the Escalating Impacts of Heatwaves. New York: UNICEF, 2022.

4) Ortiz-Bobea, Ariel, Trevor R. Ault, Carolyn M. Carrillo, Robert G. Chambers, and David B. Lobell. "Anthropogenic Climate Change Has Slowed Global Agricultural Productivity Growth." Nature Climate Change 11 (2021): 306–12.

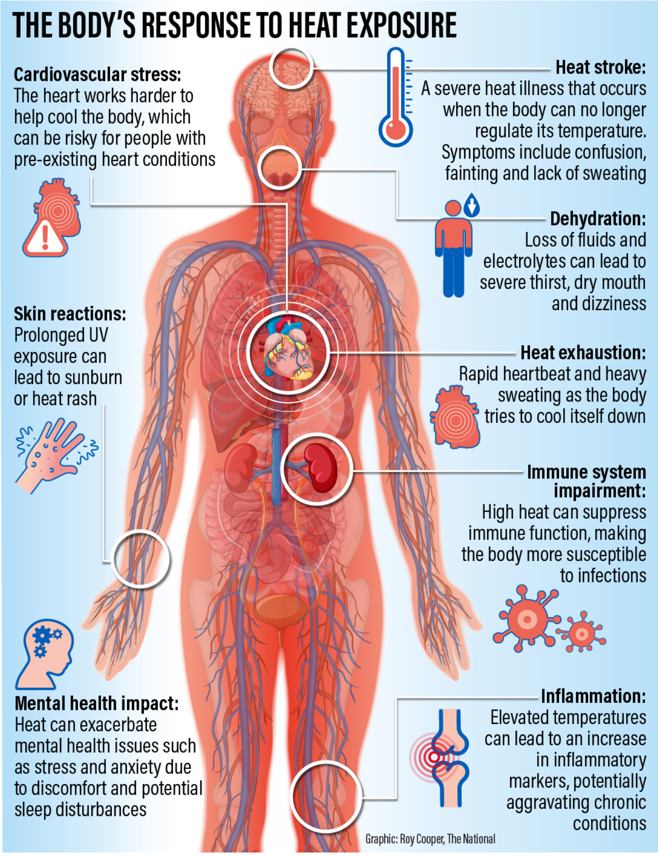
5) Kjellström, Tord, Nicolas Maître, Catherine Saget, Matthias Otto, and Takhmina Karimova. Working on a Warmer Planet: The Impact of Heat Stress on Labour Productivity and Decent Work. Geneva: International Labour Organization, 2019.

6) Callahan, Christopher W., and Justin S. Mankin. "Globally Unequal Effect of Extreme Heat on Economic Growth." Science Advances 8, no. 43 (2022): eadd3726.

7) Woetzel, Lola, Dickon Pinner, Hamid Samandari, Hauke Engel, Mekala Krishnan, Brodie Boland, and Carter Powis. Climate Risk and Response: Physical Hazards and Socioeconomic Impacts. McKinsey & Company, January 16, 2020.

Heatwaves are often called 'silent disasters' because their lethal impact—ranging from severe heat stress to organ failure and death—usually goes unnoticed. Vulnerable groups such as children, the elderly, outdoor workers, pregnant women, and those with chronic conditions bear the brunt of these events (Nitschke, Tucker, and Bi 2007; Hansen et al. 2008). Beyond causing health crises, extreme heat can disrupt food security by reducing crop yields, lowering livestock productivity, and worsening water scarcity (Chaudhury, Gore, and Sinha Ray 2000; Dash and Mamgain 2011).

Figure 2 How heat impacts the human body



Source: Hassan, Marwa. "Feeling the Heat? It Might Be Making You More Prone to Illness." The National, March 19, 2024.

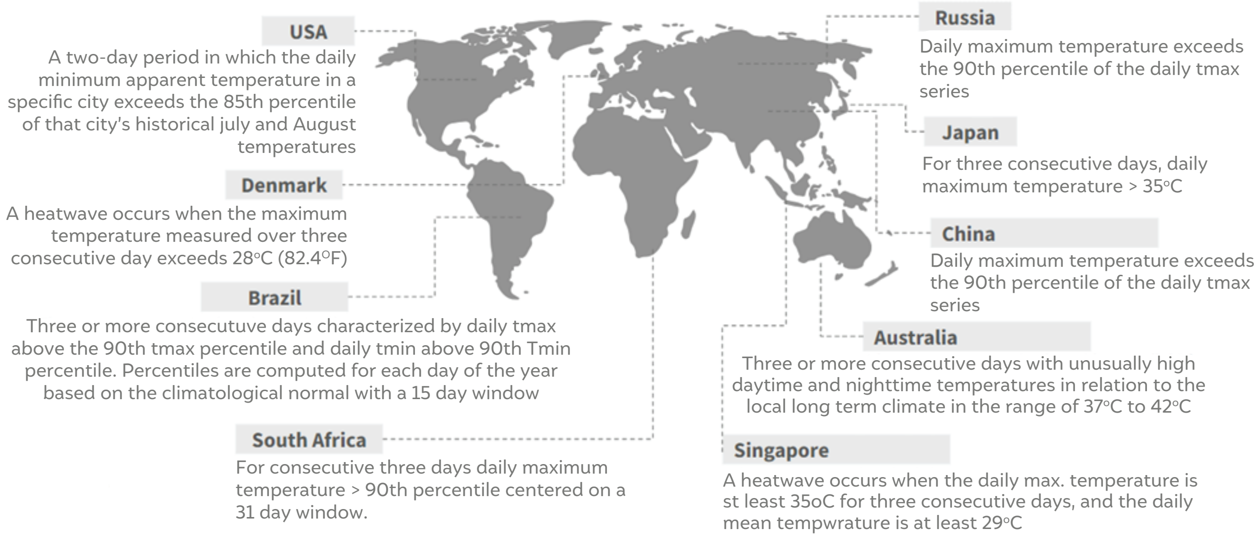
Extreme heat is a slow-onset hazard with uneven impacts across different population groups. Building resilience requires granular, local insights on the interplay of rising heat hazards, exposure levels, and inherent vulnerabilities. To strengthen decision-making, we have developed a district-level heat risk index (HRI) that offers a comprehensive view of heat risks, enabling targeted resilience-building strategies.

1.1 Understanding the difference between heatwaves, heat stress, and heat risks

Heatwaves, heat stress, and heat risks are related to extreme heat and are often used interchangeably. Though related, these terms are different from each other. Heatwaves do not have a universal definition. They are characterised by an unusually hot period, with different countries using varying criteria to measure these extreme weather events. In contrast, heat stress occurs when the body temperature exceeds 37°C in humans and animals—the temperature at which the body in unable to effectively remove excess heat. This causes discomfort, heat cramps, and exhaustion, and—in severe cases, when it exceeds 40°C—heatstroke. Heat risks arise from the interplay between the heat hazard (often intensified by factors such as high humidity and low rainfall), the exposure of people or systems, their vulnerabilities (shaped by socio-economic, physical, and institutional factors), and their capacity to adapt and cope.

Heatwaves—purely a weather phenomenon—lack a standardised measurement criterion and a globally uniform definition. The World Meteorological Organization (WMO) characterises a heatwave as "*five or more consecutive days of prolonged heat in which the daily maximum temperature is higher than the average maximum temperature by 5°C (9°F).*" However, the definition and criteria for gauging temperature extremes vary significantly worldwide. Further, they are tailored to local conditions based on climatological and impact criteria specific to each region (Alexander et al. 2006; Vose, Easterling, and Gleason 2005).

Figure 3 **Heatwave criteria and definitions vary throughout the globe**



Source: Authors' compilation

Figure 4 **The India Meteorological Department defines heatwaves by how far daytime temperatures exceed normal or fixed thresholds.**

Criteria 1:	Heatwave is considered if maximum temperature of a station reaches -  40°C or more for plains  37°C or more for coasts  30°C or more for hilly regions
Criteria 2:	Once criteria 1 is satisfied, the departure from normal (calculated based on 1981-2010) should be • Between **4.5°C to 6.4°C** for a heatwave day • **More than 6.4°C** for a severe heatwave day
Criteria 3:	If criteria 1 and 2 are met in at least in **2 stations** in a Meteorological subdivision for at least **two consecutive days**, a heatwave/severe heatwave is declared on the second day

However, If the maximum temperature is ≥ **45°C and** ≥**47°C**, A heatwave and severe heatwave is directly declared.

Source: India Meteorological Department (IMD). "FAQ on Heat Wave." India Meteorological Department, n.d.

However, since last few years, the IMD has started issuing alerts based on district-wise percentiles—i.e., when the daytime and night time temperature reaches the 90th, 95th, and 98th percentiles, alerts are issued accordingly. The IMD also provides hot and humid weather and warm night forecasts as part of its mult-hazard forecast system.

1.2 State of heatwaves and extreme heat in India

In India, heatwaves—as defined by the IMD—occur most frequently during the pre-monsoon or summer months (March to June). Central and northwestern India form the ‘heatwave zone’, since this is where these events are most common. At the same time, eastern coastal areas like Andhra Pradesh and Odisha also experience periodic heatwaves (Rohini, Rajeevan, and Srivastava 2016). Each region’s heatwaves are driven by different physical factors. These incidents are on the rise—according to observational research—especially in hotspots (Pai, Nair, and Ramanathan 2013; Rohini, Rajeevan, and Srivastava 2016). For instance, heatwaves in northwest India are linked to El Niño—southern oscillation events, tropical sea surface temperature anomalies, and enduring high-pressure systems. They are also linked to decreasing soil moisture. Interestingly, heatwaves tend to be more severe in the years after an El Niño event (Ratnam et al. 2016).

Recent extreme heat events have been severe. In 2022, South Asia experienced prolonged, record-breaking heat. March 2022 was the hottest month in India since 1901, with temperatures reaching 3–8°C above average in many regions (Zachariah et al. 2022). In 2024, India faced one of its longest heatwaves, exposing over a billion people across 23 states to extreme heat. This came on the heels of unprecedented heatwaves in 2022 and 2023, when 10 states declared heatwaves. In April 2024, the IMD forecast around 20 heatwave days—well above the usual 4–8 days for the month—highlighting the rapid impact of climate change and its ties to phenomena such as El Niño (PIB 2024). By the summer of 2024, India had recorded 536 heatwave days across its meteorological subdivisions.

According to climate change projections, heat extremes in India are expected to increase in intensity, frequency, and duration, and spread across more areas (Im et al. 2017). Under a high-emission climate change scenario (RCP 8.5), average temperatures in India could rise by about 4.4°C by 2100. This could result in 55 per cent more warm days and 70 per cent more warm nights, relative to 1976–2005 (Krishnan et al. 2020). Heatwaves could occur three to four times more often, and their durations might nearly double by the late twenty-first century (MoES 2024).

The intensifying heat stress—worsened by rising humidity and urban heat islands—will have significant consequences. **Health outcomes, mortality, working conditions, and the spread of vector-borne diseases are likely to worsen, particularly in densely populated urban areas (Vaghela and Mangal 2018; Bordoloi and Saharia 2021). These escalating risks pose serious challenges to achieving the Sustainable Development Goals and the Sendai Framework for Disaster Risk Reduction, disproportionately impacting vulnerable populations and critical sectors across India.**

Heat action plans are the key policy documents guiding city, district, and state-level action on extreme heat preparedness, response, and risk mitigation

Box 1	India's 2024 heatwave and its widespread impact

In 2024, India experienced one of its longest heatwaves on record. **In Rajasthan, Churu hit 50.5°C (122.9°F)—the highest temperature recorded in eight years**—with Churu, Sirsa, and Phalodi reaching 50°C (122°F). In Delhi, areas like Mungeshpur, Narela, and Najafgarh neared 50°C on 28 May, and the capital recorded its warmest night ever at 35.2°C (95.36°F).

The extreme heat in 2024 led to over 48,000 suspected heatstroke cases nationwide. It also triggered severe water scarcity and pushed the power demand to record high levels (Patel et al. 2024). Many manufacturing companies cut working hours in May, contributing to a three-month low in new orders (S&P 2024). Additionally, rising energy demand for cooling prompted the All India Power Engineers' Federation to warn of potential blackouts on 18 June (Dhillon 2024).

Source: Authors' compilation

1.3 Why does India need a composite heat risk index to advance its resilience?

Heat is often labelled as an invisible disaster because, unlike floods or cyclones, it leaves behind no apparent physical destruction. Yet, data shows that the impact of extreme heat varies significantly, making it critical to understand who is most at risk. Heat risk hinges on three key factors: (i) the intensity of the heat (and its compounding effects such as humidity); (ii) the degree of exposure; and (iii) the underlying vulnerabilities of affected communities.

However, most studies examine only temperature trends, productivity losses, or socio-economic vulnerabilities, resulting in a fragmented view of heat risk. Despite the rising frequency, intensity, and duration of heatwaves, effective management can prevent these events. This is where heat action plans (HAPs) play a crucial role. HAPs are strategic frameworks developed by state, district, and city governments to prepare for, respond to, and recover from extreme heat.

India's experience with HAPs highlights their potential. For example, Ahmedabad—which launched its HAP in 2013—reportedly avoided about 1,000 all-cause deaths annually during 2014–2015 compared to the 2007–2010 baseline (Hess et al. 2018). However, recent reviews have identified critical gaps in some HAPs developed in India. Pillai and Dalal reported a lack of heat risk quantification in approximately 95 per cent of India's HAPs (2023). This shortcoming hinders targeted action, especially when financial resources are limited.

Box 2 **India's heat action plans and their gaps**

In 2016, the NDMA issued guidelines for creating HAPs to improve the preparedness and response capabilities of health systems and disaster management authorities. These guidelines prioritised allocating scarce healthcare, financial, informational, and infrastructure resources to safeguard the populations most at risk from excessive heat in certain jurisdictions.

The guidelines were updated in 2017 and 2019 to combine short-, medium-, and long-term heat risk mitigation techniques. The updated framework includes an eight-point checklist to build inter-agency and stakeholder coordination, develop a stakeholder responsibility matrix, map vulnerable and at-risk populations, set localised heat thresholds for early warnings, and outline strategies for monitoring, evaluation, and plan updating (NDMA n.d.).

According to publicly available data, more than 100 HAPs exist in India. However, even though NDMA's HAP guidelines are robust and require HAPs to include sections on risk quantification, a recent review of 37 plans revealed critical gaps (Figure 5). One significant gap is that nearly 95 per cent of the reviewed HAPs lack risk and vulnerability assessments (Pillai and Dalal 2023). This shortfall highlights an important area for further research, which we explore in this study.

Lack of localised heat hazard mapping	Lack of heat risk and vulnerability assessments	Lack of funding sources	Lack of strong legal foundations for implementation	Lack of monitoring, evaluation and implementation transparency
67% of HAPs only consider ambient temperature day-time extremes in definition; humidity and warm nights not considered Locally defined heat thresholds not considered	**95% of HAPs lack vulnerability assessments** List of solutions do not focus on identified vulnerable groups	**Only 30% of reviewed HAPs discuss funding sources** Majority ask implementing departments to self-allocate resources	No linkage with the legal structure for disaster management and environmental governance	Lack of repositories for access to general public Non-clarity in updation period and evaluation data

Source: Valiathan Pillai, Aditya, and Tamanna Dalal. How Is India Adapting to Heatwaves? An Assessment of Heat Action Plans with Insights for Transformative Climate Action. New Delhi: Centre for Policy Research, 2023.

We reviewed 15 publicly available state and UT-level heat action plans (as of November 2024) and found that only 2 had undertaken heat risk and vulnerability assessments. These assessments are crucial for prioritising vulnerable areas within a city, district, or state for effective resource allocation.

As of March 2025, heatwaves are not listed among the 12 disasters eligible for full funding in India's state and national disaster response funds (SDRF/NDRF), which account for 80 per cent of overall disaster management funding in the country. When states declare heatwaves as a local disaster, they can only use 10 per cent of these funds for response efforts. Further, without robust risk and vulnerability assessments, authorities struggle to identify high-risk areas, prioritise their needs, and effectively allocate limited resources. Heatwaves became eligible for funding from state disaster mitigation funds (SDMFs) in 2024, which constitutes 20 per cent of the overall disaster management fund. Funded efforts must focus on long-term, local measures to proactively reduce heat risk.

However, this means heatwaves are eligible for only 30 per cent of the overall funds available for disaster management—and only when states declare them as local disasters (15th FC 2020).

To address this gap, we developed a composite heat risk index to support decision-making and ensure efficient resource allocation based on risk profiles.

Urban areas can be up 5°C to 10°C warmer than surrounding areas, increasing the heatwave intensity and associated risks due to urban heat island effect (WMO 2024).

Image: iStock

2. Approach and methodology

Heat is a dynamic atmospheric phenomenon, and the risks it poses vary across regions and people. These risks are influenced by the intensity, frequency, and duration of heat hazards, further compounded by factors such as high relative humidity and low rainfall. Additionally, exposure levels to heat hazards and socio-economic vulnerabilities shape the overall heat risk profile of a population.

To systematically assess these risks, we developed a composite district-level HRI. Our methodology follows a structured, multi-step approach to capture the complex interactions between heat hazards, exposure, and vulnerability. Specifically, our analysis is guided by four key research questions:

- **Heat hazard trends:** How are daytime and nighttime heat extremes changing at the district level? How do factors like humidity and lower rainfall influence these trends?
- **Population exposure and vulnerability:** Who is most exposed to extreme heat and what makes some populations more vulnerable than others?
- **Current risks:** What are the present risks of extreme heat for different districts in India?
- **Risk drivers and potential solutions:** What are the key factors driving heat risk in each district and what could be the potential solutions?

This approach offers a comprehensive understanding of heat risk distribution across India and informs targeted strategies for enhancing resilience. Figure 6 presents a detailed schematic of our approach and methodology.

Figure 6 Our methodology to develop the heat risk index followed a 7-step sequential approach

Selection of the risk assessment framework

Selection of long list of indicators for hazard, exposure, and vulnerability based on systematic literature review

Finalising and assigning weightage to each indicator through an analytical hierarchy process and stakeholder consultation

Developing unified data roster sheets for hazard, exposure, and vulnerability of all districts

Min-max normalisation of indicators on a uniform scale based on their relation to risk, i.e., direct or inverse

Assigning weightage and computing the hazard, exposure, and vulnerability components

Computing the composite heat risk index

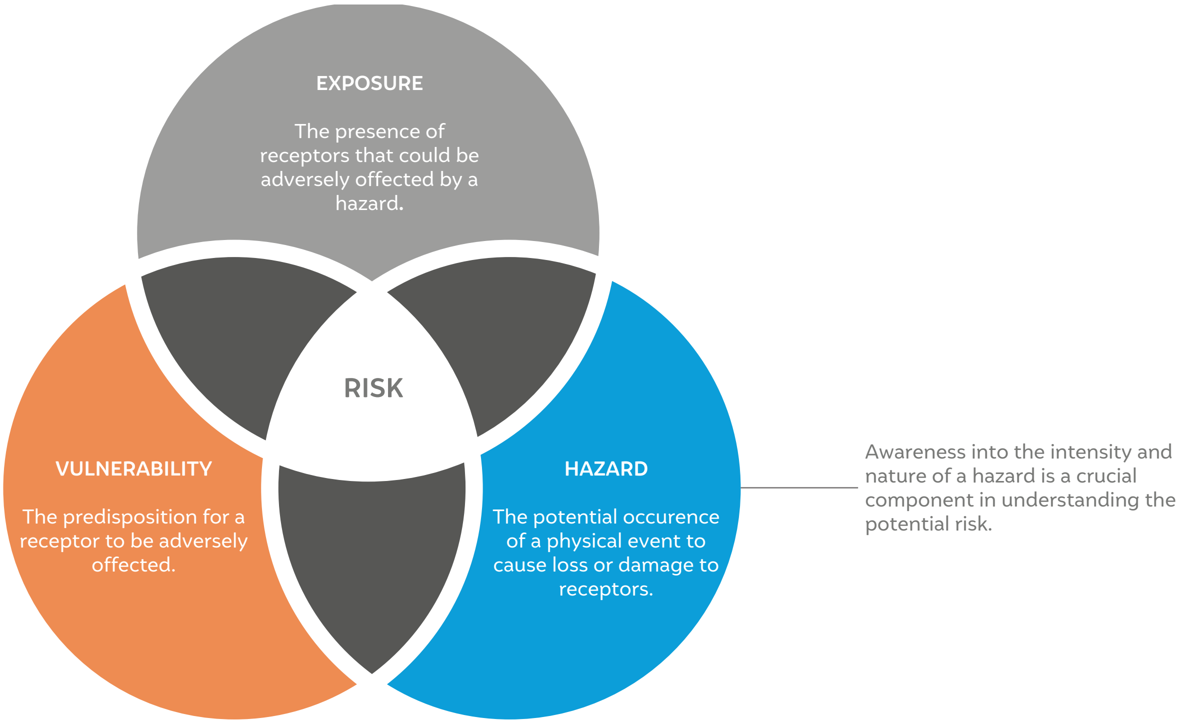
Source: Authors' compilation

2.1 The risk assessment framework

The Intergovernmental Panel on Climate Change (IPCC) serves as a global scientific body that develops risk and vulnerability assessment frameworks for climate change. Over the years, researchers have applied various methodologies—including those outlined in the IPCC Fourth Assessment Report (AR4) and Fifth Assessment Report (AR5)—to map the risks and vulnerabilities associated with different climate hazards.

For this study, we adopted the IPCC's AR5 framework (2014) to assess heat risks across Indian districts. This approach is also endorsed by the Indian Department of Science and Technology for national-level climate assessments. The framework defines risk as the result of interactions between hazard, exposure, and vulnerability, providing a structured methodology for evaluating climate-related risks. Figure 7 outlines the definitions of these components as per the IPCC (2014).

Figure 7 The Intergovernmental Panel on Climate Change's AR5 risk assessment framework



Source: Leaman, Christopher K., Mitchell D. Harley, Kristen D. Splinter, Mandi C. Thran, Michael A. Kinsela, and Ian L. Turner. "A Storm Hazard Matrix Combining Coastal Flooding and Beach Erosion." Coastal Engineering 170 (2021): 104001.

In the context of heat risk assessment, hazard refers to the potential occurrence of heat extremes or their increasing frequency and intensity. Exposure represents elements that directly increase risk from extreme heat, such as population density and building density.

The vulnerability component of the risk framework is divided into two sub-indices:

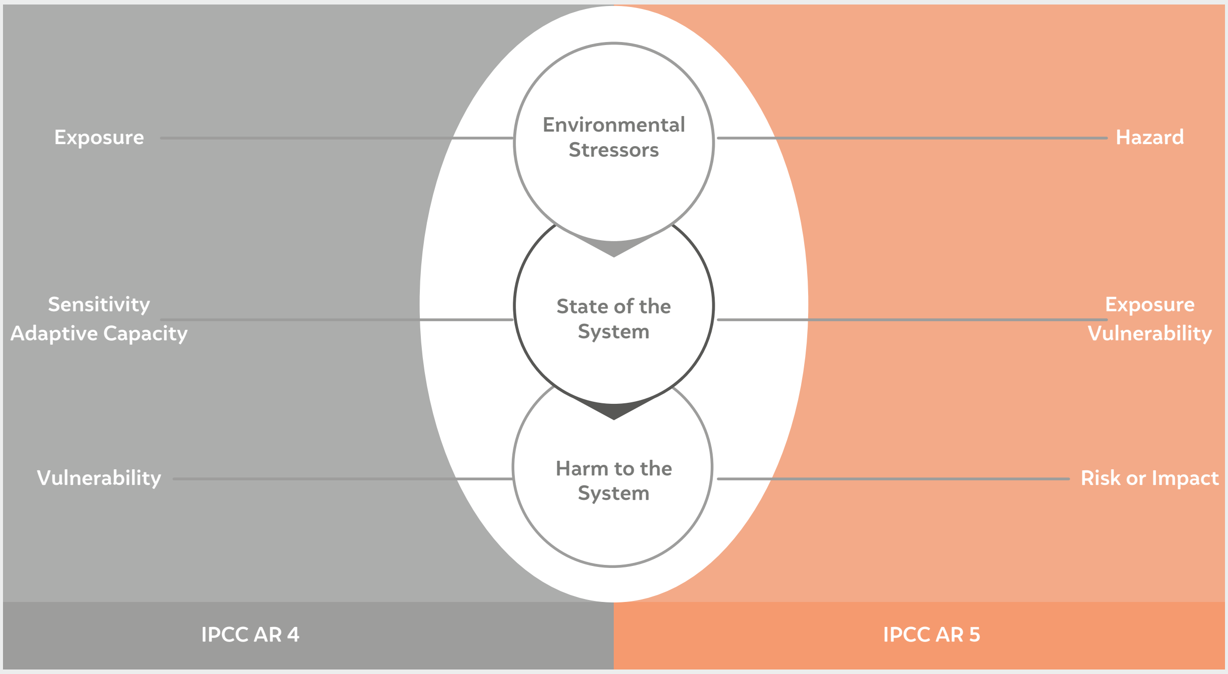
- **Sensitivity to heat risk:** This refers to the extent to which a system or population is negatively or positively affected by climate variability or change. In this case, older adults (60+ years), individuals with pre-existing health conditions, and those living in informal settlements (e.g., slum housing), exhibit higher sensitivity to extreme heat (Kenny et al. 2010; Ramsay et al. 2021).

- **Adaptive capacity to heat risk:** This is the ability of systems, institutions, and individuals to adjust, respond, or recover from heat-related impacts. In this case, access to health insurance and proximity to healthcare facilities enhance a population's capacity to cope with extreme heat events (Burton et al. 1997).

Box 3 **Understanding the risk and vulnerability frameworks of IPCC's AR4 and AR5**

The key distinction between the IPCC's AR4 and AR5 risk assessment frameworks lies in their conceptual approach. AR4 defines vulnerability as a function of exposure, sensitivity, and adaptive capacity, whereas AR5 shifts the focus to direct risk assessment by combining hazard, exposure, and vulnerability (Das et al. 2020; Fritzsche et al. 2014). This framework separates exposure from vulnerability, placing greater emphasis on the explicit calculation of risk.

Figure 8 The logical difference between AR4 and AR5



Source: Das, Shouvik, Amit Ghosh, Sugata Hazra, Tuhin Ghosh, Ricardo Safra de Campos, and Sourav Samanta. 2020. "Linking IPCC AR4 & AR5 Frameworks for Assessing Vulnerability and Risk to Climate Change in the Indian Bengal Delta." Progress in Disaster Science 7: 100110.

In AR4, the IPCC defines vulnerability as "*the degree to which geophysical, biological, and socio-economic systems are susceptible to, and unable to cope with, adverse impacts of climate change, including climate variability and extremes*" (IPCC 2007). The term 'vulnerability' in AR4 is used to describe both the vulnerable system itself (e.g., low-lying islands or coastal cities) and the impact on these systems (e.g., flooding of coastal areas and agricultural lands). According to IPCC's AR4, vulnerability is a function of three factors: exposure, sensitivity, and adaptive capacity (IPCC 2007). '*Exposure*' in AR4 refers to the magnitude and duration of climate-related stress such as a drought or change in precipitation, whereas '*sensitivity*' is the degree to which the system is affected by climate-related stress or extreme events. Adaptive capacity in AR4 refers to the system's ability to withstand or recover from extreme events or damage. The adaptive capacity of a system determines its vulnerability, by modulating exposure and sensitivity (IPCC 2007).

The IPCC's AR5 introduced a new methodology and nomenclature. This strategy is comparable to the idea of disaster risk. This is distinct from the way vulnerability is currently understood in the IPCC's AR4. IPCC's AR5 defines risk as "*the potential for consequences where something of value is at stake and where the outcome is uncertain, acknowledging the diversity of values*". It is frequently expressed as the likelihood that dangerous events or trends will occur multiplied by the consequences if they do (IPCC 2014; Das et al. 2020). Hazards associated with the effects of climate change are the main meaning of the term 'risk'.

Source: Authors' compilation

2.2 Selecting indicators, weightage, and stakeholder consultations

A comprehensive risk assessment requires multiple steps. First, goals and objectives need to be clearly defined. These goals will guide key decisions on the scale, sector, tier, indicators, and methods used to assess risk. In this study, our primary aim was to evaluate the relative heat risk for populations across Indian districts using a standardised set of indicators.

To achieve this, we identified key indicators based on three criteria:

- Their relevance to heat risk and vulnerability, ensuring alignment with the broader risk frameworks and literature.
- Availability of data across all districts to enable nationwide comparability.
- Their alignment with established risk assessment literature, particularly those suited to the Indian context.

The selection process was guided by existing studies and established frameworks that have assessed heat risk and vulnerability in India and globally. Key references include the Department of Science and Technology's *Climate Vulnerability Assessment for Adaptation Planning in India Using a Common Framework (2019–2020)*, the *National Disaster Management Plan (2019)*, the National Guidelines for Preparation of Action Plan—Prevention and Management of Heatwaves (2019), and a research paper by Azhar et al. (2017). Additionally, we reviewed HAPs available in the public domain to ensure alignment with best practices and policy frameworks.

Tables 3 to 5 provide an overview of the selected indicators, detailing their data sources, rationale, relationship to risk, and the weightage assigned to each within the overall risk quantification framework. We prioritised indicators with consistent and reliable district-level data to ensure they could be compared and rigorously analysed.

We validated selected indicators through a stakeholder consultation of experts from academia and non-governmental organisations in India. These experts represented diverse, multi-disciplinary backgrounds which included climate science, public policy, water resources, disaster management, and public health.

A critical aspect of this study was assigning relative weights to indicators across the three core components—hazard, exposure, and vulnerability—to account for their differing contributions to heat risk. Given the diverse range of indicators, we employed the analytic hierarchy process (AHP)—a structured decision-making method that enables experts to compare indicators in pairs and assign relative importance scores. It is a semi-quantitative approach that allowed us to engage stakeholders in determining the relative weights of the indicators.

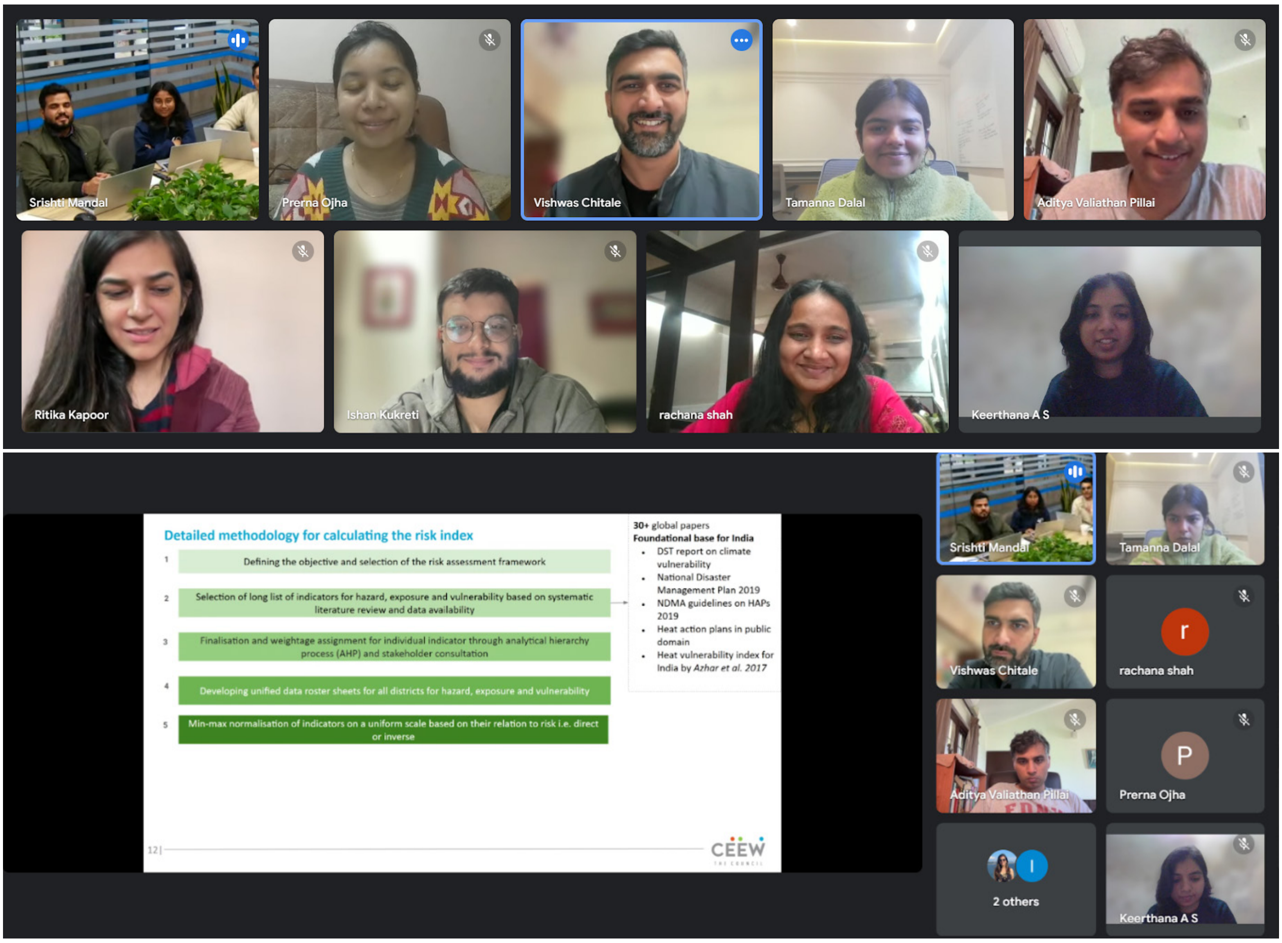


Image: CEEW

Stakeholder consultations to determine the relative weights of the indicators

The AHP method allows stakeholders to assess the relative weight of multiple criteria by making pair-wise comparisons—such as 'indicator X is more important than indicator Y'—and convert these comparisons into numerical weightings (Kaspercyk and Knickel 2022). This methodology has been widely applied in multi-criteria decision-making, planning, resource allocation, and conflict resolution (ODPM 2004).

Figure 9 We followed a six-step approach based on Analytic Hierarchy Process to calculate the weight of each indicator

Step 1: Defining the goals and indicators

- Developing heat risk index for indian districts
- IPCC AR5 framework
- Selection of indicators for hazard, exposure and vulnerability

Step 2: Structuring the hierarchy

- Level 1: heat risk index
- Level 2: hazard index, exposure index and vulnerability index
- Level 3: indicators under each component

Step 3: Developing the pairwise comparison matrix

- Pairwise comparison matrix to compare the relative importance of indicators against each other using Saaty's scale (1-9)

Step 4: Normalisation of the matrix

Divide each value in a column by the column sum to get a normalized matrix and calculate the average of each row to get the relative weight (priority) of each indicator.

Step 5: Consistency checking

- Compute the Consistency Ratio (CR)
- If CR< 0.1, the jugments are consistent. if not revise the pairwise comparisons.

Step 6: Final weight calculation

- Aggregate pairwise comparison matrices form multiple experts through geometric mean and arrive at overall weightage for each indicator.

Source: Authors' compilation

To compute indicator weights in the AHP, we constructed an n × n comparison matrix, where n represents the number of indicators within a specific risk component. We compared indicators in pairs using a predefined numerical scale within this matrix.

This scale—developed by Saaty—assigns values ranging from 1 to 9 (Table 1) to represent the relative importance of each indicator (1987). The AHP method splits the decision-making process into smaller components, allowing experts to systematically compare indicators in pairs and assign scores based on their perceived importance. This structured approach ensures that indicators are weighed consistently and transparently within the risk assessment framework.

Table 1 Saaty scale for assigning the relative importance of each indicator

Intensity of importance	Definition	Explanation
1	Equal importance	Two indicators are equally important to the objective
3	Moderate importance	As per experience and judgement, one indicator is slightly more important
5	Strong importance	As per experience and judgement, one indicator has strong importance over another
7	Very strong importance	One indicator has a much stronger importance than the other
9	Extreme importance	Evidence signalling the importance of one indicator over another is of the highest possible order of affirmation

Source: Joerin, J., and R. Shaw. "Mapping Climate and Disaster Resilience in Cities." In Climate and Disaster Resilience in Cities (Community, Environment and Disaster Risk Management, vol. 6), edited by Rajib Shaw and Anshu Sharma, 47–61. Leeds: Emerald Group Publishing Limited, 2011.

To compute the final indicator weights, we aggregated the responses from individual stakeholders to determine the weight percentage assigned to each indicator across the three risk components. We combined the twelve responses using the geometric mean method, producing a consolidated preference matrix. The resulting indicator weights fell within the range of 0 to 1.

To ensure the reliability of stakeholder judgements, we computed the consistency ratio (CR) for the 12 responses received. A CR value below 10 per cent (or less than 0.1) indicates a consistent decision matrix. In this assessment, the CR for all the consolidated matrices remained within this threshold, confirming the robustness of the weighting process. We computed the CR using a formula where λ represents the maximum eigenvalue of the matrix and n denotes the number of indicators:

$$CR = \frac{(\lambda - 1)}{(n - 1)}$$

Table 2 The consistency ratio for hazard, exposure, and vulnerability (sensitivity + adaptive capacity) was found to be below 10%, showing consistency across responses

Component	Sub-component	Consistency ratio (%)
Hazard		3.32
Exposure		0.79
Vulnerability	Sensitivity	1.58
	Adaptive Capacity	4.33

Source: Authors' analysis

2.3 Mapping the heat hazard

A key component of this study is the detailed mapping of heat hazards, which is foundational for assessing heat-related risks. Since heat is a slow-onset and dynamic phenomenon, capturing its variability and compounding effects requires a structured and nuanced approach. This necessitates the definition of precise thresholds and criteria for hazard indices to ensure a robust and comprehensive assessment.

To achieve this, we developed a long-term dataset to track extreme heat occurrence not only in traditionally high-risk regions such as northwest India but also in areas which are not heat-prone but are now experiencing increasing heat extremes. Our methodology accounts for the changing characteristics of heat hazards by analysing shifts in key indices over the last decade (2012–2022) compared to the climatic baseline (1982–2012). This approach allowed for a more comprehensive and data-driven analysis of evolving heat risks.

We mapped heat hazards using a step-by-step methodology, ensuring consistency and accuracy in capturing emerging heat trends across different regions.

We began by reviewing the existing literature on the methodologies used to measure extreme heat. Our analysis revealed that researchers employ various approaches to define and quantify heat extremes, each with varying thresholds and metrics. A summary of these methodologies is presented in Box 4.

Box 4 **Mapping heat hazard in literature**

Extreme heat events are assessed and monitored using various indices, each designed to capture different aspects of heat intensity and its impact on human health and the environment. One commonly used metric is the percentile threshold of maximum temperature (Tmax90 or Tmax95), which identifies unusually high temperatures based on a 2-day or 5-day moving window (Rohini, Rajeevan, and Srivastava 2016). In Europe, heatwaves are defined as "three consecutive summer days with maximum temperatures exceeding the 80th percentile" (Heo, Bell, and Lee 2019). A global urban study considered heatwaves as events where daily maximum temperatures exceeded the 99th percentile for at least six consecutive days.

Another key index is the excessive heat factor, developed by Nairn and Fawcett (2015) and Perkins and Alexander (2013). This metric combines two components—excess heat and heat stress—to assess the intensity and persistence of extreme heat events.

Studies worldwide have established strong correlations between high temperatures and adverse health outcomes, including increased mortality and morbidity (Heo, Bell, and Lee 2019). This highlights the need for better understand linkages between heatwaves and their health impacts to develop effective prevention strategies. Many countries have implemented heat-health warning systems based on guidelines set by the WMO and the World Health Organization (WHO). These systems use thermal comfort indices that incorporate meteorological parameters such as air temperature, humidity, and wind speed to assess perceived heat stress.

Commonly used indices include:

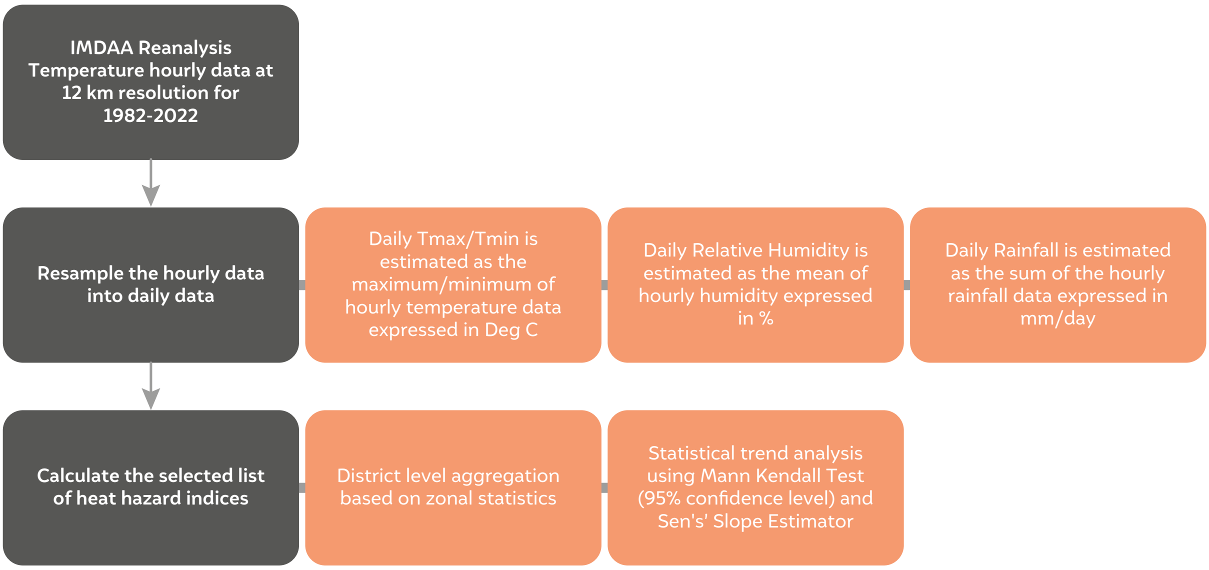
- **Heat index (HI):** combines air temperature and relative humidity to estimate perceived heat stress.
- **Wet bulb globe temperature (WBGT):** accounts for air temperature, humidity, wind speed, and solar radiation to evaluate actual human heat exposure.

In the Indian context, Srivastava, Kumar, and Mohapatra (2024) developed a framework for hot weather analysis that incorporates maximum and minimum temperatures, relative humidity, wind speed, and heat persistence using station-based observations across the country. This framework has been adopted by the IMD to issue heat alerts. The IMD uses both official criteria (outlined in Section 1.1) and experimental indices (such as percentile-based thresholds and the heat index) to enhance heat risk assessment and forecasting.

Source: Authors' compilation

To conduct a comprehensive analysis of heat trends, we developed long-term daily gridded datasets using data from the Indian Monsoon Data Analysis and Assimilation (IMDAA) project to examine trends over 1982–2022. IMDAA provides data at a spatial resolution of 12 km, making it the most suitable dataset for district-level assessments and the highest resolution dataset available for the Indian subcontinent (Rani et al. 2021). We used the 95th percentile as the threshold for very hot days and very warm nights, which is found to be a good indicator of extreme heat events (Cardil, Terrén, and Kobziar 2014; Avashia, Garg, and Dholakia 2021; Tiwari 2023).

Figure 10 **Schematic representation of heat hazard calculation from IMDAA data**



Source: Authors' compilation

IMDAA is a collaborative effort between the Meteorological Office, UK, the National Centre for Medium Range Weather Forecasting, India, and the IMD. It is financially supported by the *National Monsoon Mission* of the Indian government's Ministry of Earth Sciences (NCMRWF n.d.). For validation purposes, we also utilised the 100-km resolution gridded dataset developed by Srivastava, Rajeevan, and Kshirsagar (2009), ensuring consistent trend estimation and reliable results. We calculated the indices outlined in Table 3 using this data.

Box 5	IMDAA reanalysis data

For this study, we used the **IMDAA dataset, a high-resolution reanalysis product. Reanalysis datasets combine numerical weather prediction models with observations from various sources such as satellites and ground-based stations. The models create the initial estimates, which are then corrected for bias using observational data. In contrast, observed datasets are created entirely from values that were recorded at actual observation stations and then interpolated onto a grid.**

Bias adjustment is necessary to increase the accuracy of reanalysis datasets because they are obtained from model simulations. To ensure consistency with recorded data, this correction is incorporated into the system setup and—in the case of IMDAA—is matched with IMD's observation stations.

Several evaluations have validated the accuracy of IMDAA data, highlighting its ability to capture key weather patterns across different seasons. This dataset has demonstrated strong alignment with both observational datasets (e.g., IMD station data) and global reanalysis datasets such as ECMWF Reanalysis v5 (ERA5). While IMDAA's fine spatial resolution makes it particularly suitable for district-level climate assessments, it is important to assess its ability to accurately replicate meteorological trends across India.

A study by Rani et al. (2021) assessed IMDAA's performance in representing seasonal weather phenomena across India by comparing it with IMD's observational data. Their findings indicate that IMDAA effectively captures the major characteristics and seasonal variability of the Indian monsoon, with results comparable to those obtained using ERA5 reanalysis data. However, when compared to IMD's observational data, the IMDAA dataset exhibits a slight cool bias in winter and a warm bias in summer.

Despite these minor deviations, IMDAA remains a reliable high-resolution reanalysis dataset for studying weather and climate trends over the Indian subcontinent (Rani et al. 2021; Ashrit et al. 2020; Mahmood et al. 2018; Singh et al. 2021).

Source: Authors' compilation

Table 3 Twelve hazard indices were used to quantify heat from IMDAA data, capturing relative humidity, rainfall, and the frequency, intensity, and duration of day and night heat extremes.

Code	Indicator	Calculation	Rationale	Weightage (%)	Relation to heat risk
H1	**Increase in frequency of very hot days**	Number of days exceeding the 95th percentile of maximum temperature (Tmax) for the 1982–2011 baseline.	A higher frequency of very hot days is a direct indicator of increasing heatwaves, leading to heightened heat stress, particularly for outdoor workers.	17	Direct
H2	**Increase in frequency of very warm nights**	Number of nights exceeding the 95th percentile of minimum temperature (Tmin) for the 1982–2011 baseline.	Warmer nights exacerbate chronic health conditions and reduce overall resilience to heat, as they prevent the human body from cooling down after daytime heat exposure.	15	Direct
H3	**Increase in relative humidity**	Percentage change in daily average relative humidity compared to the 1982–2011 baseline.	High humidity impairs the body's ability to cool through sweating, amplifying heat stress. Even at moderate temperatures, high relative humidity significantly increases heat-related impact.	12	Direct
H4	**Increase in duration of hot spells**	The average length of spells when the number of consecutive days where both Tmax and Tmin exceed the 90th percentile threshold of the 1982–2011 baseline.	Prolonged hot spells—even at lower intensity—create cumulative stress on the human body, increasing the risk of heat-related illnesses over time.	10	Direct
H5	**Decrease in diurnal temperature range**	Change in the difference between Tmax and Tmin for the summer season.	Reduced diurnal range correlates with higher heat stress and lower recovery potential during the night.	6	Direct

Code	Indicator	Calculation	Rationale	Weightage (%)	Relation to heat risk
H6	**Peak daytime temperature**	Historically highest one-day Tmax is during the summer season.	Extreme daytime and nighttime temperatures increase the risk of heatstroke and heat-related illnesses. These indicators also help identify historically hottest regions and maximum temperature extremes that a district may experience.	4	Direct
H7	**Peak nighttime temperature**	Historically highest one-night Tmin is during the summer season.		5	
H8	**Increase in the average of 10 hottest days**	Change in the average Tmax of the 10 hottest days each summer.	An increase in the average of the 10 hottest days and nights reflects intensifying heat hazards, capturing both shifts in heat intensity and duration.	7	Direct
H9	**Increase in the average of 10 hottest nights**	Change in the average Tmin of the 10 hottest nights each summer.		7	
H10	**Early onset of heat season**	Date of first occurrence of Tmean exceeding the 95th percentile threshold for the month of March.	Earlier heat season onset can strain resources and increase risks for those unprepared for prolonged exposure to high temperatures.	7	Direct
H11	**Delay in withdrawal of heat season**	Date of last occurrence of Tmean exceeding the 95th percentile threshold for the month of June.	Delayed heat season withdrawal extends the number of days people are exposed to high temperatures, increasing cumulative heat stress well into June and beyond.	6	Direct
H12	**Decrease in total summer rainfall**	Change in total rainfall during the summer season compared to the baseline of 1982–2011.	Reduced rainfall heightens heat stress risks—particularly due to delayed monsoon onset and water shortages—compounding the impact of extreme heat.	4	Direct

Source: Authors' analysis

For the final stage of the analysis, we conducted a district-level assessment using the indices outlined in Table 3 to evaluate heat hazards in terms of their frequency, intensity, and duration. These indices were calculated using the Xclim library and combined with the Xarray module in Python (a programming language) to process the gridded climate data. Next, we aggregated the computed indices at the district level using a spatial zonal statistics method. This method overlays the gridded data onto district boundaries and identifies the grids falling within each district.

We delineated district boundaries using the Survey of India (SOI) shapefile, which provides geographic information system boundaries for approximately 734 districts across India, as of March 2025. This approach enabled us to conduct a localised assessment of heat hazards, allowing for a granular understanding of regional variations in heat risk across the country.

Following the estimation of heat indices, it was necessary to assess whether individual climatic indices exhibited a statistically significant trend that increased or decreased over the time for each district. This was achieved by applying the Mann-Kendall trend test, a non-parametric method widely used for detecting trends in time-series data at a 95 per cent confidence level (Mann 1945; Kendall 1975). We selected the Mann-Kendall test due to its suitability to analysing meteorological data, as it does not assume a normal data distribution. This makes it ideal for detecting trends in climatic indices (Meals et al. 2011). Unlike least-squares regression—which may be influenced by extreme values—the Mann-Kendall test is a rank-based method, ensuring robustness against outliers. The test computes Kendall's Tau rank correlation coefficient, which ranges between -1 and 1. A positive value indicates an increasing trend, while a negative value signifies a decreasing trend (Meals et al. 2011). To quantify the rate of change, we also estimated Sen's slope, which represents the median slope across all pairs of data points in the time series (Meals et al. 2011).

The test uses a null hypothesis—that no trend exists—to determine statistical significance. A trend is considered statistically significant if the p-value is less than 0.05. The Mann-Kendall test has been extensively applied in meteorological and hydrological studies due to its effectiveness in detecting climate-related trends (Kumari et al. 2022; Mohan and Rajeevan 2017).

2.4 Developing the exposure and vulnerability indices

To generate information on exposure and vulnerability, we used a combination of geospatial datasets, Census 2011 data, and data from the National Family Health Survey (NFHS) 2019–2021.

For several exposure and vulnerability indicators such as population density, we relied on Census 2011 estimates. We projected these estimates for until 2022 by analysing the rate of change between the Census 2001 and 2011 estimates. We applied the compound annual growth rate method to estimate the demographic data for 734 districts as per the SOI's official shapefile. For districts that were formed after Census 2011 and NFHS 2019, we used the area apportionment method of assigning demographic data based on the parent district's population trends. To ensure accuracy, we refined the dataset using GIS shapefiles, socio-economic reports, and Census district handbooks.

We used three datasets for indicators requiring geospatial analysis such as built-up density, green cover, and building footprint density: i) Sentinel 2A-based, ESRI-generated land use and land cover (LULC) data at a 10-metre spatial resolution; ii) normalised difference vegetation index (NDVI) and modified normalised difference vegetation index (MNDWI) based on Landsat 8 data at a 30-metre spatial resolution; and iii) Google's building footprint data for the entirety of India, processed at a bounding box of 500 sq m.

Next, we aggregated these indices at the district level using the zonal statistics method, ensuring spatial consistency in exposure estimates. For vulnerability indicators, we primarily relied on Census 2011 and NFHS 2019–2021 datasets. Additional indicators such as the availability of health centres were sourced from the Indian government's Open Government Data Platform, along with other national and regional datasets.

Tables 4 and 5 provide the sources, temporal coverage, and spatial resolutions of all selected indicators.

Table 4 Three indices were used to map heat exposure

Code	Indicator	Calculation and source	Rationale	Weightage (%)	Relation to heat risk
E1	**Population density**	Population divided by the total area of the district based on Census 2011 projections.	Higher population density increases heat exposure, as more people are concentrated within a smaller area, amplifying heat-related risks.	46	Direct
E2	**Building density**	Number of buildings per 500 sq.m. calculated from 2024 Google building footprint data at 30-metre spatial resolution.	Higher building density is interpreted as a proxy for increased population concentration due to residential and commercial developments. It also strongly correlates with urban heat stress, since dense built environments limit natural cooling mechanisms such as ventilation and green spaces.	36	Direct
E3	**District gross domestic product (DGDP)**	Actual value of DGDP at constant rates from the State Handbook of Districts 2013–2022.	High economic activity indicates greater potential financial losses from extreme heat events, affecting productivity, infrastructure, and overall economic resilience.	18	Direct

Source: Authors' analysis

Table 5 Twenty indicators were used to map vulnerability—12 for sensitivity and 8 for adaptive capacity.

Sensitivity (vulnerability)					
Code	**Indicator**	**Calculation and source**	**Rationale**	**Weightage (%)**	**Relation**
S1	**Labour population**	Percentage of total number of agricultural workers and main cultivators to the total working population as defined in Census 2011.	As outdoor labourers, agricultural workers and main cultivators experience prolonged exposure to extreme heat, increasing their susceptibility to heat-related illnesses, dehydration, and productivity losses.	7	Direct
S2	**Total number of disastrous heatwave days**	Total number of heatwave days (as per IMD criteria) that have led to at least one human death as per IMD's *Hazard and Vulnerability Atlas 2022*.	Developed by the IMD, this indicator is based on the occurrence of at least one heatwave-related human fatality. It serves as a proxy for heat-related mortality, providing insights into the sensitivity of districts by identifying areas with a history of heatwaves resulting in human deaths.	8	Direct
S3	**Change in land use and land cover**	Based on Landsat 8 satellite imagery data from 2005 and 2023, we used the increase in built-up area and the decrease in vegetation cover as indicators.	Increased built-up areas and reduced vegetation or water bodies amplify heat risks by intensifying the urban heat island effect, reducing natural cooling through evapotranspiration and exposing more people to extreme temperatures.	10	Direct
S4	**Young population (below 5 years)**	Percentage of young population to the total population as defined by Census 2011 projections.	A higher percentage of young children indicates a demographic that may be more vulnerable to heat stress.	12	Direct
S5	**Old population (above 65 years)**	Percentage of old population to the total population as defined by Census 2011 projections.	Older adults are more susceptible to heat-related illnesses; a higher percentage of elderly individuals suggests an increased risk of heat stress in the population.	11	Direct
S6	**Scheduled Caste**	Percentage of SC population to the total population as per Census 2011.	People belonging to SCs often face socio-economic disadvantages, limiting their access to resources and protective measures against heat stress which increases their vulnerability.	7	Direct
S7	**Sex ratio**	Sex ratio calculated as per Census 2011.	A low sex ratio increases heat vulnerability since women—especially pregnant and elderly women—face higher health risks from extreme heat due to physiological sensitivity, limited access to healthcare, and socio-economic constraints.	8	Direct
S8	**Scheduled Tribe**	Percentage of ST population to total population as per Census 2011.	People belonging to STs may face higher exposure to heat stress due to geographical, economic, and social disadvantages, including inadequate healthcare access.	8	Direct
S9	**Household members with pre-existing non-communicable illnesses (all in %)**	As per NFHS-5 data (2019–2021), we used Anaemia, blood pressure (Hypertension), and blood sugar levels (Diabetes) as indicators.	Individuals with pre-existing non-communicable illnesses are particularly vulnerable to climate and environmental stressors since their health conditions can worsen under extreme heat, making them less resilient.	12	Direct
S10	**Persons with disability**	Percentage of persons with disability to the total population as defined by Census 2011.	Individuals with disabilities may have reduced mobility and higher vulnerability to heat stress, especially without access to cooling resources.	5	Direct

Sensitivity (vulnerability)					
Code	**Indicator**	**Calculation and source**	**Rationale**	**Weightage (%)**	**Relation**
S11	**Marginal workers**	Number of marginal workers to the total working population as defined by Census 2011.	A high number of marginal workers indicates economic instability and limited access to health resources, increasing the impact of heat stress.	5	Direct
S12	**Temporary and semi-permanent houses**	Number of temporary and semi-permanent houses in proportion to the total number of houses as per Census 2011.	A higher number of temporary or semi-permanent houses has been interpreted as a proxy for slum households, i.e., inadequate housing conditions. This increases the risk of heat-related health issues in informal settlements.	7	Direct

Adaptive capacity (vulnerability)						
Code	**Indicator**	**Calculation and source**	**Data source and year**	**Rationale**	**Weightage (%)**	**Relation**
AC1	**Literacy rate**	Percentage of literate individuals to the total population.	Census 2011	Lower literacy rates may hinder awareness and understanding of heat-stress risks and prevention measures, leading to increased vulnerability.	10	Inverse
AC2	**Population with electricity access**	Percentage of households with electricity to the total number of households.	NFHS-5, 2019–2021	Limited electricity restricts the use of cooling appliances, increasing heat-stress risks during high-temperature periods.	9	Inverse
AC3	**Improved drinking-water access**	Percentage of households with improved sources of drinking water located in the premises as per NFHS-5 and NSSO.[1]	NFHS-5 and NSSO data for 2019–2021	Safe drinking water is crucial for hydration during heat waves; a lower percentage indicates a higher risk of heat-related illnesses.	15	Inverse
AC4	**Green spaces**	Percentage of geographical area under green cover calculated by NDVI at a 30-metre resolution.	Landsat 8 data, 2024	Higher NDVI values indicate more green spaces, which reduce urban heat islands and mitigate heat stress in surrounding populations.	19	Inverse
AC5	**Water resources**	Percentage of geographical area under water bodies calculated by MNDWI at a 30-metre resolution.	Landsat 8 data, 2024	Higher MNDWI values reflect greater water availability essential for cooling and hydration; areas with insufficient water resources are more vulnerable.	8	Inverse
AC6	**Healthcare centres**	Number of healthcare centres per 1,000 people.	CEEW 2024 compilation based on PMGSY[2] rural dataset, India's open government data platform, PMJAY[3] website, National Medical Commission, and Railway Authority of India.	Increased access to healthcare centres is essential for addressing heat-related illnesses; fewer facilities increase morbidity risks during heat events.	19	Inverse

1 NSSO stands for National Sample Survey Office.
2 PMGSY stands for Pradhan Mantri Gram Sadak Yojana, a scheme launched by the Indian government's Ministry of Rural Development in 2000 to develop road connectivity for rural areas across the country.
3 PMJAY stands for Pradhan Mantri Jan Arogya Yojana, a national public health insurance scheme launched by the Indian government's Ministry of Health and Family Welfare in 2018.

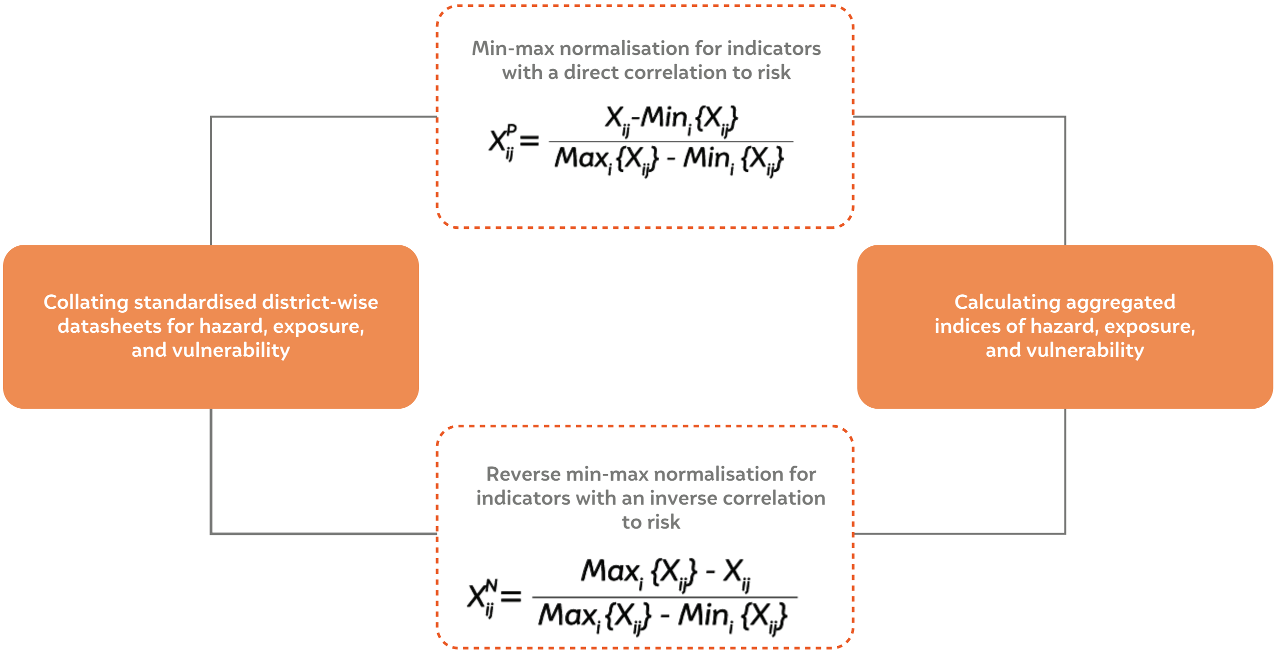
Adaptive capacity (vulnerability)						
Code	**Indicator**	**Calculation and source**	**Data source and year**	**Rationale**	**Weightage (%)**	**Relation**
AC7	**Workers under MGNREGA[4]**	The total number of workers enrolled under MGNREGA in 2024 summer.	MGNREGA, 2024	The availability of guaranteed employment under MGNREGA helps workers adapt to livelihood disruptions caused by environmental or economic shocks. Providing income stability and local work opportunities enhances their ability to cope with stressors, thereby reducing their overall vulnerability.	9	Inverse
AC8	**Health insurance**	Number of people enrolled under PMJAY for 2024.	PMJAY National Health Authority dashboard, 2024	Enrolling for PMJAY ensures access to affordable healthcare for vulnerable populations to enhance their resilience to health-related shocks.	11	Inverse

Source: Authors' compilation

2.5 Developing the composite heat risk index

Following the development of datasets for the exposure, hazard, and vulnerability components, we normalised all indicators based on their relationship to heat risk—whether they are direct or inverse. We normalised indicators with an inverse relationship to risk using the min-max normalisation technique.

Figure 11 **Schematic representation of the development of sub-component-wise indices**

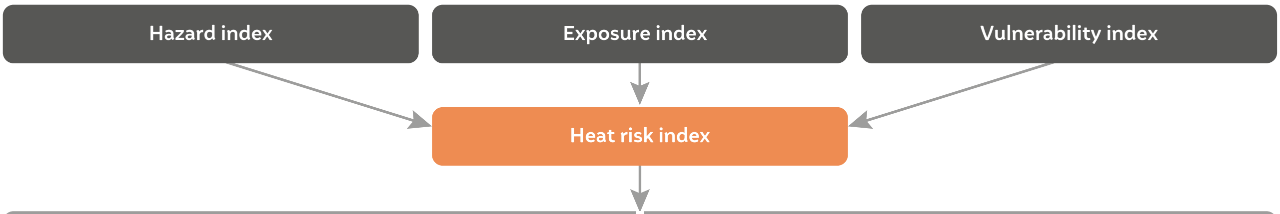


Source: Authors' compilation

4 MGNREGA stands for Mahatma Gandhi National Rural Employment Guarantee Act, 2005. This law guarantees at least 100 days of assured wage employment in a financial year to at least one member of every Indian rural household whose adult members volunteer to do unskilled manual work.

After normalising the indicators, we applied weights to each of them and computed sub-component scores for each district. We derived these scores by multiplying the sub-component scores and normalising them using the min-max scale to ensure consistency across districts. We used this methodology to compute the HRI. We classified districts using the natural breaks method into very low, low, moderate, high, and very high risk categories. We assigned each district a score ranging from 1 to 5 to enhance interpretability based on risk levels. For state-level aggregates, we first aggregated district-level scores using a simple mean approach. Next, we identified the percentage of districts falling under the high and very high risk categories to constitute state-level rankings. This also provided a broader assessment of heat risk at the state level.

Figure 12 A schematic representation of our methodology to obtain the heat-risk scores for each district



Heat risk index category	Heat risk score
Very low	1
Low	2
Moderate	3
High	4
Very high	5

Source: Authors' compilation

To analyse the drivers of heat risk in greater detail, we identified key contributing factors in high and very high risk districts. Indicators with normalised values equal to or above 0.8 were considered primary contributors to heightened risk levels. We have provided these insights in state-level handbooks for decision-makers (Annexure 1).

It is important to note that districts classified as very low or low risk are not entirely free from heat risks. Rather, their classification indicates that they are at relatively lower risk compared to other districts on a comparative scale.

2.6 Limitations of the methodology

This study maps extreme heat risks to the population by focusing on their exposure and outlines strategies for disaster risk reduction and public health resilience. However, our HRI does not include sector-specific indicators for agriculture, water, biodiversity, or power—a limitation we acknowledge. However, our findings lay the groundwork for the future development of sector-specific risk indices.

Further, we have relied on socio-economic and demographic data from the Census 2011 and projected these figures to 2022 using accepted statistical methods. While this data is outdated, no newer comprehensive survey is available.

Additionally, our risk assessment is based on a fixed set of indicators chosen through an extensive literature review and stakeholder consultations. Any changes to this set could alter the results.

Urban areas can be up 5°C to 10°C warmer than surrounding areas, increasing the heatwave intensity and associated risks due to urban heat island effect (WMO 2024).

Image: iStock

3. Results and discussion

In this section, we provide the findings from the analysis of heat hazard, exposure, vulnerability, and the composite HRI quantified for the summer months of March to June.

3.1 Changing patterns of heat hazard in India

Indian climate science has shown the significant impact of heat on various sectors and public health, with trends and hotspot analysis emerging as critical research areas. Most studies are based on the IMD's 100-km gridded observation data, or in some cases, ERA-5 reanalysis data. In contrast, the indigenous IMDAA dataset—available at a 12-km resolution from IMD and NCMRF[5]—has been predominantly used to assess monsoon trends. Its application for heat hazard analysis has been limited. This section presents our key findings derived from an analysis of India's IMDAA reanalysis data.

For our analysis of heat hazards, we moved beyond using fixed temperature thresholds (such as 40°C, 30°C, or 37°C) and instead used district-specific thresholds based on percentiles. A percentile is a way to rank temperatures by comparing them to historical data. For example, if the 95th percentile is 38°C in a region, it means that 95 per cent of the time, temperatures are below 38°C, and anything above it is unusually hot for that area. This locally adaptive approach—endorsed by WHO, WMO, and IMD—ensures that risk assessments reflect regional climate conditions and acclimatisation levels.

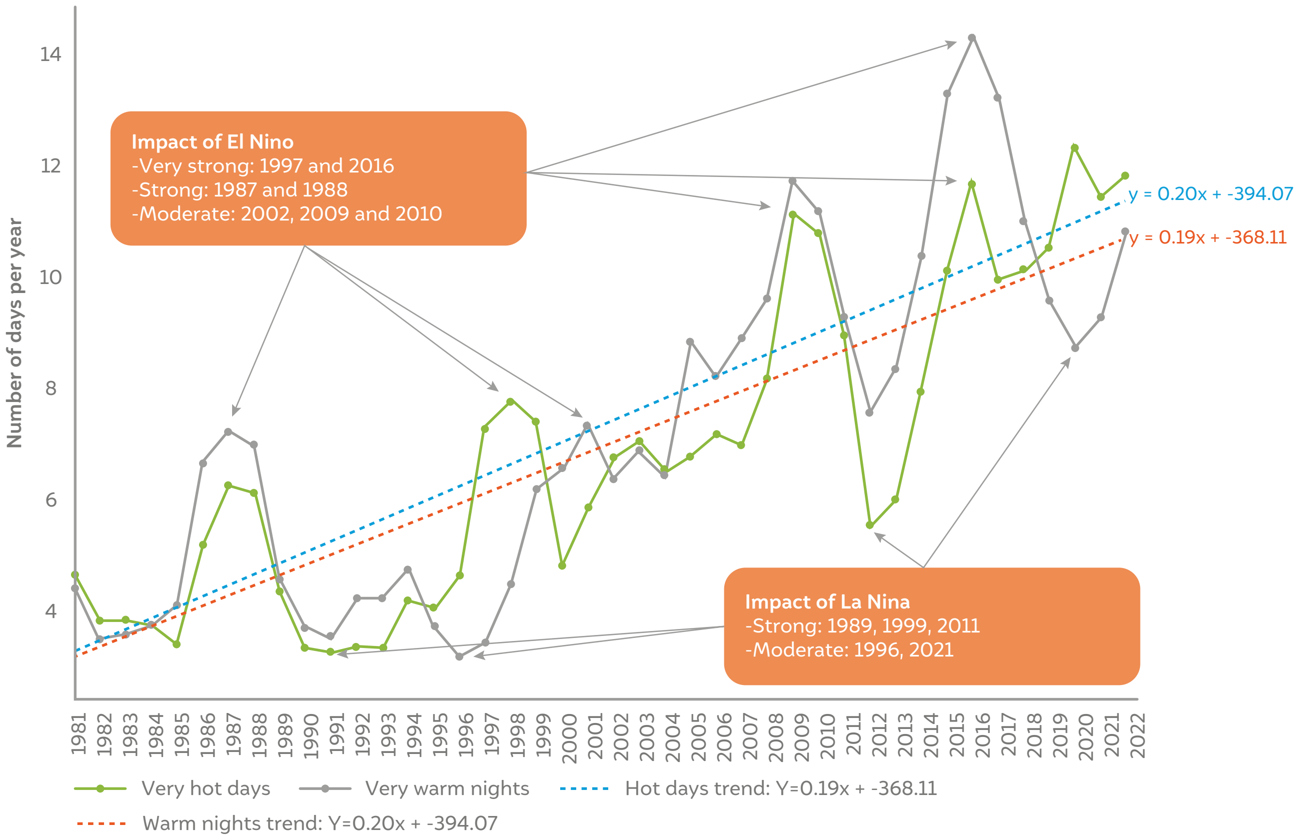
Image: iStock

Globally, heatwaves remain the deadliest natural hazard, having claimed around 4,89,000 lives annually between 2000 and 2019 (UN 2024)

5 NCMRF stands for National Centre for Medium Range Weather Forecasting.

Shifting patterns of daytime and nighttime heat extremes and intra-day temperature variability

Figure 13 In the last decade (2012–2022), India recorded up to four more very hot days and five more very warm nights each summer, as compared to the climatic baseline (1982–2011)



Source: Authors' analysis

Our analysis indicates a linear increase in heat extremes across India. Considering national average data over the past 40 years (1981–2022), the number of very warm nights is rising at a faster rate than very hot days—particularly during the last decade. Very warm nights and very hot days are both defined as instances when temperatures exceed the 95th percentile of historical data. This phenomenon is influenced by natural variability, driven by El Niño and La Niña events (see Figure 14). For example, during strong El Niño years such as 1997 and 2016, the frequency of both very hot days and very warm nights was markedly higher than the average. This trend is especially concerning because elevated nighttime temperatures impede the body's ability to recover from daytime heat, thereby increasing health risks—particularly among vulnerable groups.

Box 5 **Understanding La Niña and El Niño-southern oscillations**

In addition to climate change, **natural global weather patterns also influence heat events**. Under normal Pacific conditions, trade winds drive warm surface waters westward from the coast of South America towards Asia, facilitating upwelling, i.e., the ascent of cold, nutrient-rich water. The El Niño-southern oscillation that disrupts this equilibrium manifests in two distinct phases. El Niño (the warm phase) is marked by anomalously high sea surface temperatures in the eastern tropical Pacific, typically persisting for less than a year and occurring more frequently. Conversely, La Niña (the cool phase) is characterised by below-average sea surface temperatures and can extend over one to three years. Both phases generally peak during the Northern Hemisphere winter, influencing global weather patterns, wildfire risks, ecosystem dynamics, and economic activities (NOAA n.d.).

Source: Authors' compilation

In the last decade (2012–2022), district-level extreme heat trends have shifted significantly (see ES Figure 1) as compared to the climatic baseline (1982–2011). Over 70 per cent of Indian districts now experience at least five additional very warm nights per year, while 28 per cent of districts experience an increase of more than five very hot days annually. The rise in very warm nights is particularly pronounced in high-density urban districts (population exceeding 1 million), with Mumbai recording 15 additional warm nights per year, followed by Bengaluru (11), Bhopal (7), Jaipur (7), Delhi (6), and Chennai (4). Given that more than half of India's population is projected to reside in urban areas by 2050, this trend signals a critical challenge. The urban heat island effect exacerbates nighttime temperatures. Cities absorb and retain heat during the day, which delays cooling after sunset.

Further, more than 20 per cent of districts have recorded simultaneous increases in very hot days and very warm nights, i.e., more than five instances of each per year. This is particularly evident along the western coastline and in Jammu & Kashmir and Ladakh. In Ladakh—a key renewable energy hub—both indicators have risen sharply, with an increase of over 15 days annually.

The increasing frequency of hotter days and warmer nights in India is a well-documented trend, with multiple studies reporting consistent findings. Krishnan et al. observed that between 1901 and 2018, India's average temperature increased by approximately 0.7°C (2020). This warming is primarily attributed to greenhouse gas emissions, though it has been partially offset by the cooling effects of anthropogenic aerosols and LULC changes. Similarly, Panda, AghaKouchak, and Ambast found that heatwaves and warm spells exhibit distinct spatial and temporal patterns, aligning with model projections (2017). Notably, the 1998 warming hiatus period highlighted changes in heatwave characteristics, with drought conditions amplifying these trends.

Additionally, Mukherjee and Mishra (2018) examined climate model simulations and historical observations from the Coupled Model Intercomparison Project 5 and the Climate of the 20th Century Plus Detection and Attribution project. According to their findings, anthropogenic emissions are the major reason for the notable increase in concurrent hot day and hot night (CHDHN) events throughout India. The frequency of three-day CHDHN episodes is expected to increase fourfold by the middle of the century and twelvefold by the end of the twenty-first century under the high-emission scenario (RCP 8.5), highlighting the mounting effects of climate change.

In addition to climate change, urbanisation has emerged as a significant driver of warming, particularly for nighttime temperatures. Concrete surfaces absorb and retain heat during the day, releasing it gradually after sunset. This process contributes to the urban heat island effect, where urban areas consistently record temperatures higher than rural ones.

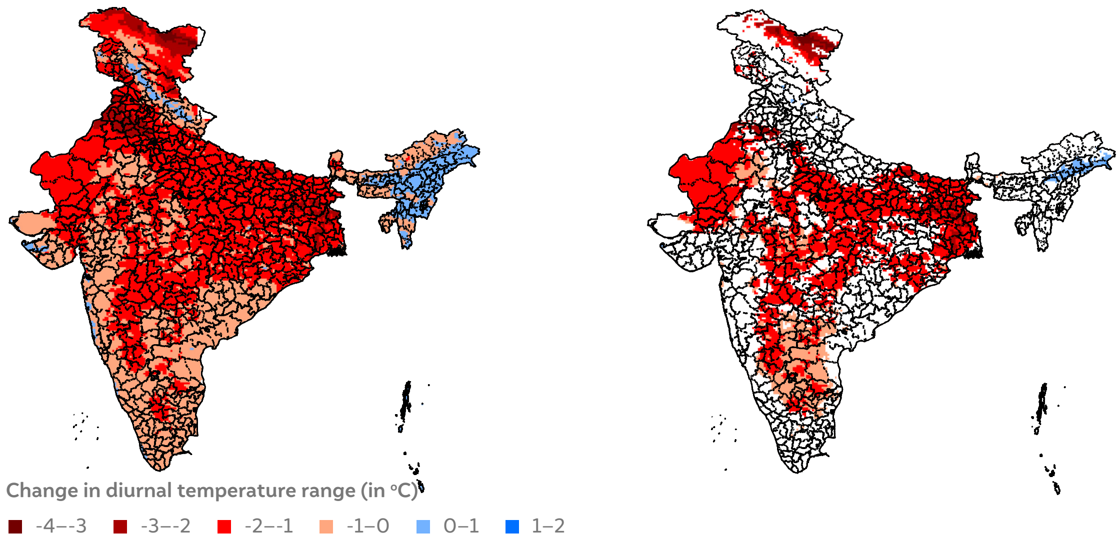
A recent analysis by Sethi and Vinoj (2024) highlights the role of urbanisation in amplifying warming trends. They estimate that urban expansion alone has led to a 60 per cent increase in warming across Indian cities. The effect is most pronounced in eastern tier-II cities, which have experienced the highest rates of urban-driven temperature rise.

To further examine the rising trend in very warm nights, we analysed the diurnal temperature range (DTR)—the difference between the daytime maximum and nighttime minimum temperature. Typically, peak daily temperatures occur in the afternoon as the atmosphere continues to absorb heat beyond noon, while minimum temperatures are recorded around dawn following the sustained loss of heat through the night. DTR is a key indicator of climatic change and serves as a critical thermal metric for assessing the impact on agriculture and human health.

Figure 14 The diurnal temperature range has reduced in almost 86% of Indian districts, especially in the last decade (2012–2011) compared to the climatic baseline (1982–2011)

a) Changes in DTR in the last decade (2012–2022) compared to the climatic baseline (1982–2011)

b) Statistically significant trends in DTR on 40 years' continuous time-series at a 95% confidence level



Source: Authors' analysis

Our analysis shows that most Indian districts have experienced a decline in DTR, with only 14 per cent recording an increase. The most pronounced reductions are observed in Punjab, West Bengal, Uttar Pradesh, Bihar, and Haryana—all agriculturally significant states—primarily due to an increase in minimum temperatures (Tmin) coupled with a slight decline in maximum temperatures (Tmax). These findings are consistent with Mall et al., who identified rising Tmin as a key driver of DTR reductions between 1991 and 2016 (2021).

A declining DTR (narrowing temperature gap) is typically driven by rising nighttime temperatures, which prevent the human body from cooling down after hot days. Studies have linked a declining DTR with an increase in all-cause and cardiovascular mortality. Further, changes in DTR influence vector-borne diseases such as malaria and dengue, since mosquito-breeding cycles are sensitive to temperature. A declining DTR reduces grain-filling durations in staple crops like wheat, rice, and maize, leading to lower yields. Warmer nights also increase plant respiration rates, leading to higher energy loss and reduced photosynthesis efficiency.

Changes in duration and intensity of hot spells

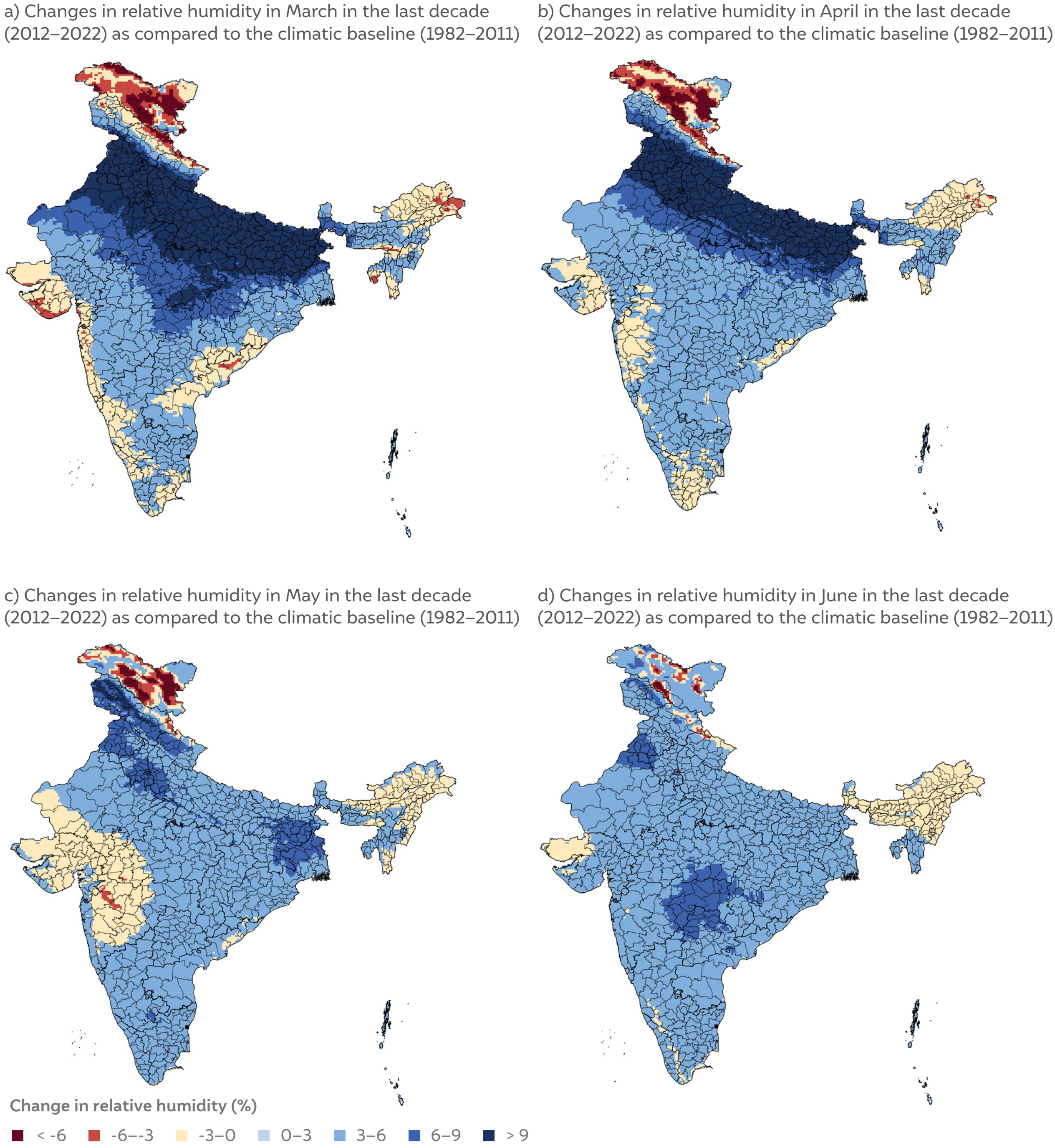
While the frequency of very hot days and very warm nights has increased, capturing the persistence and intensity of heat hazards requires a broader assessment. To this end, we define a hot spell as consecutive days during which daytime and nighttime temperatures exceed the 90th percentile threshold. Prolonged periods of extreme heat can impact human health just like isolated extreme temperature events. Additionally, we examined changes in the average temperature of the 10 hottest days and the 10 warmest nights over time.

Our findings indicate that over the last decade (2012–2022), hot spell durations have increased by more than three days in 38 per cent of districts, relative to the baseline period (1982–2011). This trend is particularly evident in districts across Gujarat, Punjab, Karnataka, Tamil Nadu, Delhi, Uttar Pradesh, Madhya Pradesh, and Rajasthan. However, in terms of heat intensity, the increase remains relatively modest. The temperature rise in the 10 hottest days ranges from 0.4°C to 1°C, while the increase in the average temperature of the 10 warmest nights is slightly higher—between 0.4°C and 1.2°C. These findings suggest that while heat events are becoming more frequent and prolonged, their intensity has not increased substantially.

Changing patterns of relative humidity

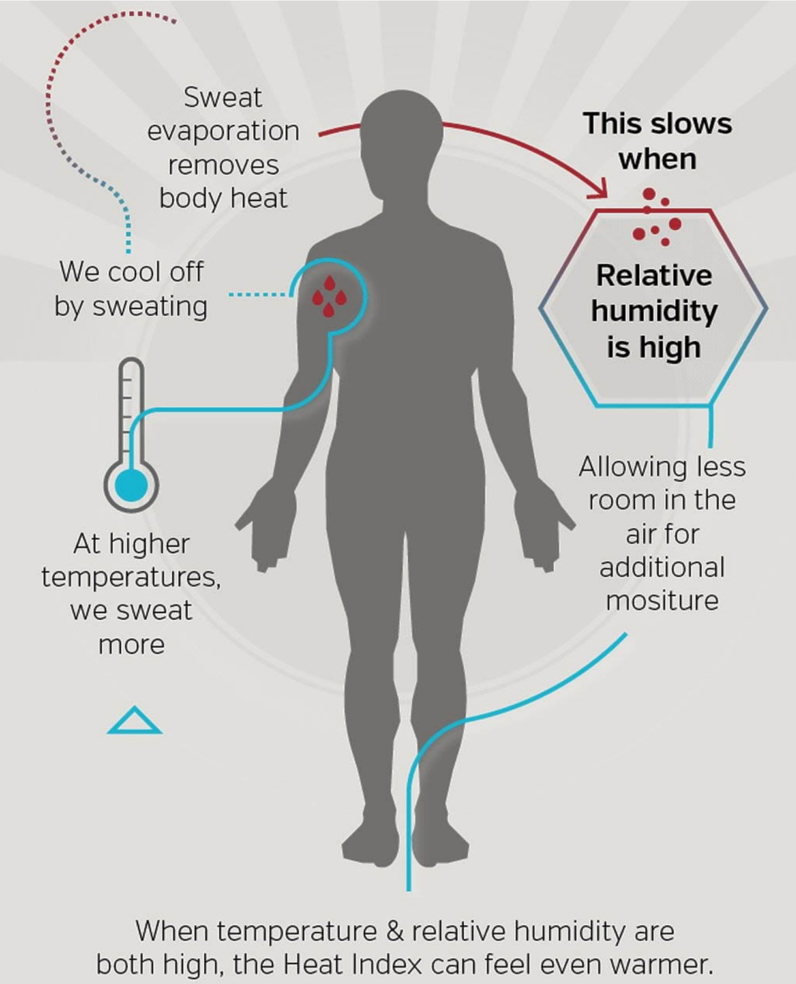
Relative humidity is an essential indicator of the compounding effects of extreme heat. When the body temperature exceeds 37°C, sweating helps cool it down. However, high humidity slows this process, making it harder for the body to release heat (Figure 17).

Figure 15 Majority of India has seen an increase in relative humidity across summer months (March to June)



Source: Authors' analysis

Figure 16 Relative humidity can significantly increase heat stress on human bodies



Source: Bear, Michael. 2019. "Extreme Heat." Safety Blog, June 7, 2019.

The analysis of relative humidity (RH) has been a key gap in existing literature, primarily due to the limited availability of dense observational network data and the reliance on ERA-5 reanalysis datasets, where RH is derived from dew point temperature rather than direct observations. This study utilises IMDAA data to examine changes in average RH across the four peak pre-monsoon months—March, April, May, and June.

Relative Humidity (RH) is defined as the ratio of actual vapour pressure (e) in the air to the saturation vapour pressure (es).

$RH = e / e_s$.

RH varies both diurnally and seasonally and is inversely related to air temperature (T a), as es increases with rising temperatures.

Rising global temperatures have led to an increase in evaporation, which in turn has increased humidity in many regions (Held and Soden 2006). Elevated atmospheric humidity reduces the body's ability to cool itself through sweat evaporation, aggravating heat strain and increasing health risks.

Many studies have assessed humidity-induced heat stress using Steadman's heat index, which integrates air temperature and relative humidity to quantify the perceived temperature or 'feels-like' effect (Steadman 1979). However, the validity of Steadman's heat index is limited in the Indian context, particularly in interior regions such as Central and Northwest India, where summer air temperatures often exceed 26°C and relative humidity frequently drops below 40 per cent. Previous studies have noted this limitation (Ganguly et al. 2009; Mahapatra et al. 2018).

We found that the average relative humidity has increased by more than 4 per cent in 50 per cent of Indian districts over the last decade (2012–2022) as compared to the long-term average (1982–2011). This trend is particularly significant in North India—especially in the Indo-Gangetic Plains (see ES Figure 4)—where agricultural workers spend long hours outdoors. Delhi has experienced a nearly 9 per cent increase in relative humidity. Coastal areas typically experience 60–70 per cent relative humidity during summer. In North India, summer relative humidity was normally around 30–40 per cent. However, relative humidity levels are now reaching 40–50 per cent, exacerbating heat stress—particularly in May and June.

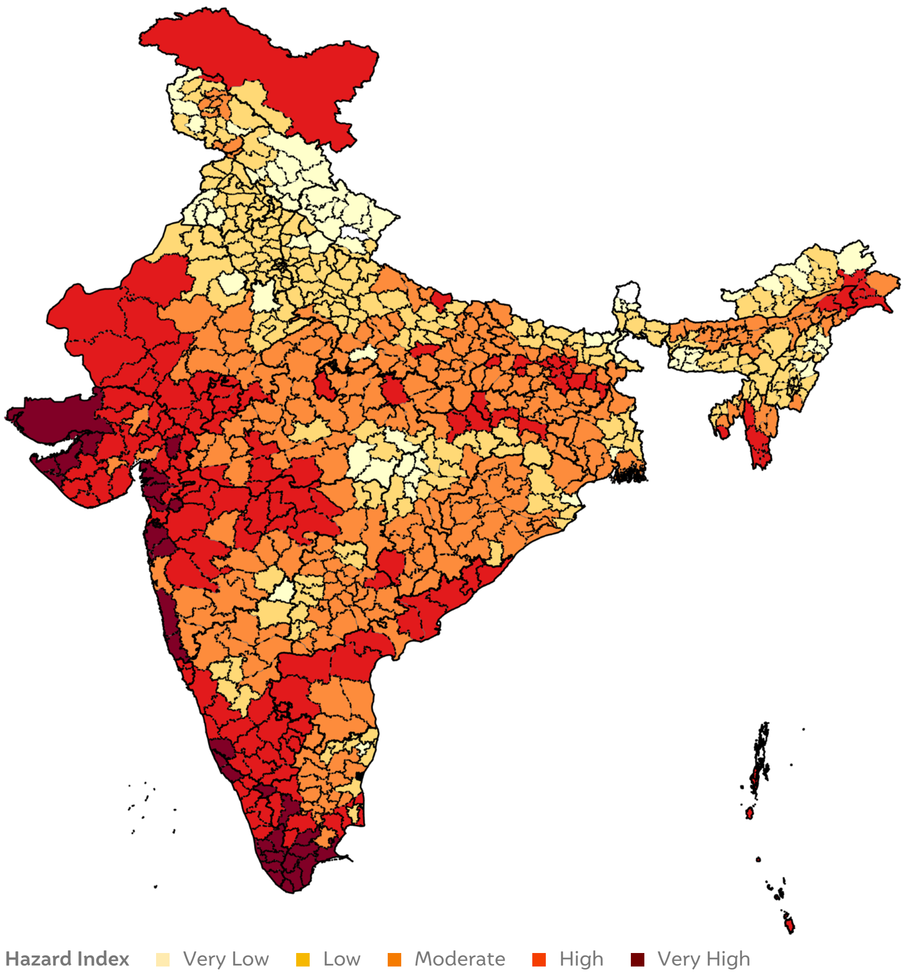
The findings of our study align with previous research, notably by Jaswal and Koppar (2011), who analysed data from 215 meteorological stations across India. Over 90 per cent of stations showed a statistically significant increase in specific humidity, relative humidity, and the dry bulb temperature, with the most noticeable increases occurring during the summer months. Their trend analysis from 1969 to 2007 offers compelling evidence of rising air moisture content. The north, northwest, central, and southeast regions of India experience the greatest, most consistent increase in specific humidity and relative humidity. In contrast, Northeast India and Jammu & Kashmir were observed to have declining relative humidity. These findings are in line with our study.

Studies attribute higher evapotranspiration rates to climate change, the urban heat island effect, irrigation practices, and horticultural activities, particularly in northern India (Bal, Prasad, and Vinod 2022).

3.2 Sub-component-wise findings from the indices for hazard, exposure, and vulnerability

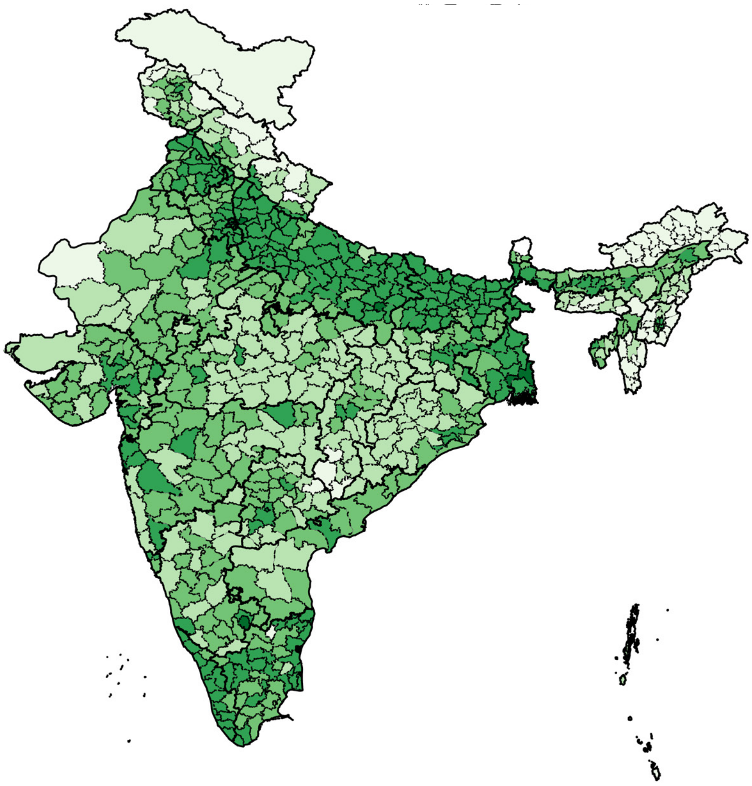
We constructed hazard, exposure, and vulnerability indices as key sub-components of the composite HRI. We derived the index by applying weighted scores to individual hazard indicators, ensuring a comprehensive representation of heat risk factors. Figures 18 to 20 present the individual findings from all three indices, providing a detailed assessment of the factors that contribute to overall heat risk.

Figure 17 Heat hazard levels are the highest in districts of the western coast, Central Maharashtra, Rajasthan, Gujarat, and Peninsular India



Source: Authors' analysis

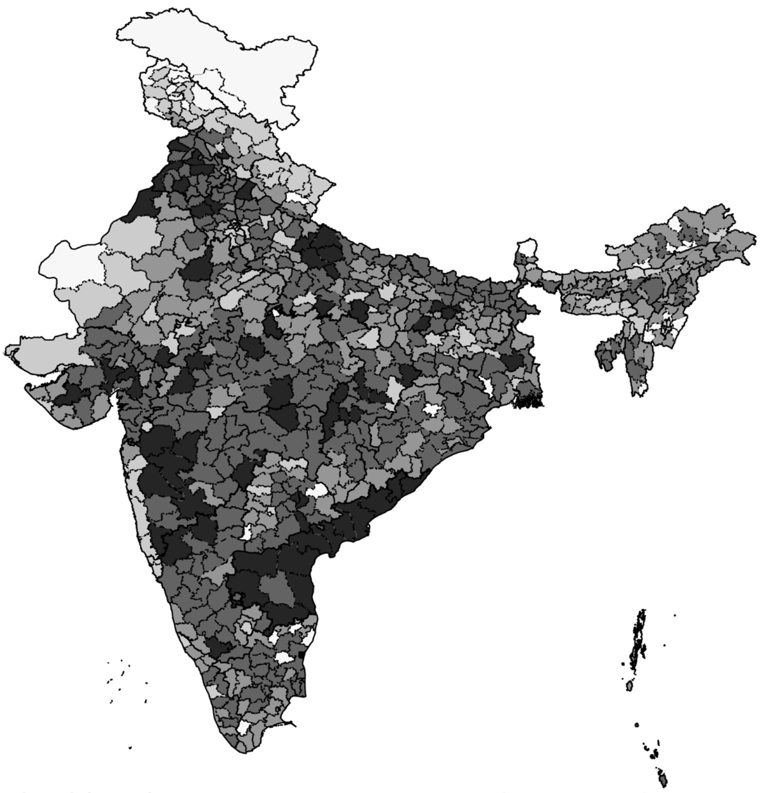
Figure 18 Exposure levels are highest in densely populated urban areas like Mumbai and Delhi, and in populous states such as Uttar Pradesh and Bihar



Exposure Index ▪ Very Low ▪ Low ▪ Moderate ▪ High ▪ Very High

Source: Authors' analysis

Figure 19 Vulnerability levels are the highest in districts across Andhra Pradesh, Central Maharashtra, Vidarbha, Chhattisgarh, and the Indo-Gangetic Plains



Vulnerability Index ▪ Very Low ▪ Low ▪ Moderate ▪ High ▪ Very High

Source: Authors' analysis

Aggregating the climatological analysis of heat patterns, our findings indicate that the heat hazard index is highest in districts along the western coast and Peninsular India. This trend is primarily driven by the increasing frequency of very warm nights and a declining DTR. Additionally, Rajasthan, Vidarbha, and Andhra Pradesh rank high on the index due to their historic susceptibility to extreme heat, since plains geography creates favourable conditions for prolonged heat events. In contrast, hilly regions generally exhibit low to very low heat hazard levels, except Arunachal Pradesh—the only state in Northeast India that the IMD has classified as heatwave-prone.

These findings underscore shifting patterns in extreme heat in India, extending beyond historically known hotspots such as Vidarbha to include coastal districts, which are emerging as significant heat prone areas.

Land and coastal heatwaves are increasing under the influence of global warming. Atmospheric research reveals that coastal heatwaves—characterised by elevated humidity—can exacerbate the effects of extreme temperatures on human health. In India, heatwaves tend to emerge in the northwest and propagate towards the northeast or southeast, which highlights the need to study how heatwaves evolve, keeping in mind the difference between coastal and land heatwaves (Dar and Apurv 2024; Zhang, He, and Guan 2025).

While heat hazard analysis forms the foundation of this study, it is the interactions between hazard, exposure, and vulnerability that ultimately determine heat risk. Our analysis shows that exposure—defined by population density, building density, and gross district domestic product—is highest in districts across the Indo-Gangetic Plains as well as in metropolitan regions such as Mumbai, the National Capital Territory of Delhi, and Kolkata. High population density and economic activity amplify the impact of extreme heat, putting more people and livelihoods at risk.

We identified districts in central Maharashtra, Andhra Pradesh, Chhattisgarh, Punjab, Haryana, Uttar Pradesh, and Bihar as high to very high in terms of vulnerability.

In these regions, vulnerability is driven by two key factors.

Sensitivity

Districts in central Maharashtra, Vidarbha, and Andhra Pradesh exhibit high sensitivity due to the presence of a large outdoor working population that is predominantly engaged in agriculture and thus more susceptible to heat stress. Additionally, empirical studies in India have identified the eastern zone as the most vulnerable area in the country (Biswas and Nautiyal 2023). The Department of Science and Technology's study, *Climate Vulnerability Assessment for Adaptation Planning in India Using a Common Framework*, highlights that the states with relatively high vulnerability are located in the eastern parts of the country, namely, Jharkhand, Mizoram, Orissa, Chhattisgarh, Assam, Bihar, Arunachal Pradesh, and West Bengal (DST 2020).

These findings are reflected in the IMD's historical disastrous heatwaves data, documented in its *Climate Hazards and Vulnerability Atlas of India*. Andhra Pradesh ranks the highest among Indian states with 700–1,000 heatwaves days between 1969 and 2019, each associated with at least one fatality.

Health and socio-economic vulnerabilities

In Punjab, West Bengal, Kerala, Karnataka, and Tamil Nadu, vulnerability is linked to a high prevalence of non-communicable diseases such as anaemia, hypertension, and diabetes, which exacerbate heat-related health risks. Chhattisgarh's vulnerability is notably high due to its large ST and SC population. Social and economic discrimination has limited their access to adaptive resources.

Conversely, districts demonstrate lower vulnerability when their population's adaptive capacity is high. Key determinants of adaptive capacity include: i) high green cover, which moderates local temperatures; ii) greater availability of healthcare infrastructure, measured as the number of health centres per 1,000 people; iii) widespread household electrification, which ensures access to cooling mechanisms; and iv) improved access to drinking water within the household premises. These factors help lower vulnerability scores in several districts, highlighting the critical role of infrastructure, healthcare, and access to basic services in mitigating heat risk.

3.3 Composite heat risk index

This section presents the findings from our composite HRI for all Indian districts. We derived the index by aggregating the values of its key sub-components—hazard, exposure, and vulnerability—as per the IPCC AR5 risk assessment framework.

Hazard, exposure, and sensitivity (part of vulnerability) positively correlate with risk, meaning that higher values of these components contribute to increased heat risk. In contrast, adaptive capacity (part of vulnerability) negatively correlates with risk, indicating that districts with greater adaptive capacity experience lower heat risk. While declining adaptive capacity amplifies risk, reductions in hazard, exposure, and sensitivity mitigate the overall risk from extreme heat. ES Figure 2 presents the district-level HRI for India, and Table 6 provides the state-wise aggregated findings.

Table 6 Aggregated findings and ranks of states and UTs on the heat risk index

State	Zone	Overall rank on the HRI	Percentage of districts falling in each category of HRI				
			Very low	Low	Moderate	High	Very high
Andhra Pradesh	South	1	0	0	0	62	38
Goa	West	1	0	0	0	0	100
Kerala	South	1	0	0	0	7	93
Maharashtra	West	1	0	0	0	22	78
Gujarat	West	2	0	0	3	21	76
Rajasthan	West	3	0	0	6	73	21
Karnataka	South	4	0	0	7	60	33
Tamil Nadu	South	5	0	0	11	43	46
Uttar Pradesh	North	6	0	0	24	71	5
Bihar	East	7	0	2	24	66	8
Telangana	South	8	0	0	30	43	27
Madhya Pradesh	Central	9	0	1	29	35	35
Punjab	North	10	0	0	41	59	0

State	Zone	Overall rank on the HRI	Percentage of districts falling in each category of HRI				
			Very low	Low	Moderate	High	Very high
Chhattisgarh	Central	11	0	0	48	52	0
Haryana	North	11	0	0	50	50	0
Odisha	East	12	0	0	53	43	4
Tripura	Northeast	13	0	12	50	38	0
Jharkhand	East	14	0	0	71	29	0
West Bengal	East	15	9	13	52	26	0
Uttarakhand	North	16	0	0	92	8	0
Assam	Northeast	17	76	18	3	3	0
Arunachal Pradesh	Northeast	18	28	68	4	0	0
Himachal Pradesh	North	18	0	83	17	0	0
Manipur	Northeast	18	0	81	19	0	0
Meghalaya	Northeast	18	18	73	9	0	0
Mizoram	Northeast	18	0	0	100	0	0
Nagaland	Northeast	18	0	100	0	0	0
Sikkim	Northeast	18	25	25	50	0	0

UT	Zone	Overall rank on the HRI	Percentage of districts in each HRI category				
			Very low	Low	Moderate	High	Very high
Dadra & Nagar Haveli	West	1	0	0	0	0	100
Daman & Diu	West	1	0	0	0	100	0
Delhi	North	1	0	0	0	45	55
Puducherry	South	2	0	0	25	50	25
Andaman & Nicobar	South	3	0	0	67	33	0
Jammu & Kashmir	North	4	0	27	68	5	0
Chandigarh	North	5	0	0	100	0	0
Ladakh	North	5	0	0	100	0	0
Lakshadweep	South	5	100	0	0	0	0

Source: Authors' analysis

Rising global temperatures have led to an increase in evaporation, which in turn has increased humidity in many regions (Held and Soden 2006).

Image: iStock

4. Study utility, recommendations, and way forward

Our study found that 57 per cent of Indian districts, home to 76 per cent of India's total population, are currently at high to very high heat risk. All government authorities—at the state, district, and city levels—must plan for extreme heat risk mitigation, preparedness, response, and relief. As recommended by the *NDMA Guidelines*, this issue is primarily addressed through HAPs in India.

This study provides actionable insights to inform heat risk—based decision-making across key sectors including:

- Water—to assess and manage water scarcity risks;
- Agriculture—to map risks to outdoor workers and crop productivity;
- Health—to understand the direct impact on public health;
- Power—to estimate cooling and electricity demand.

This study's key objective is to support agencies such as SDMAs as well as district- and city-level authorities in developing more effective, data-driven HAPs. Insights from our study can help agencies recognise key risk drivers and prioritise financial resources accordingly. To facilitate this, we have developed state- and UT-specific handbooks (Annexure 1), which include heat risk trend analyses, maps, and data visualisations. Agencies can directly leverage these resources to inform HAP development and other policy documents.

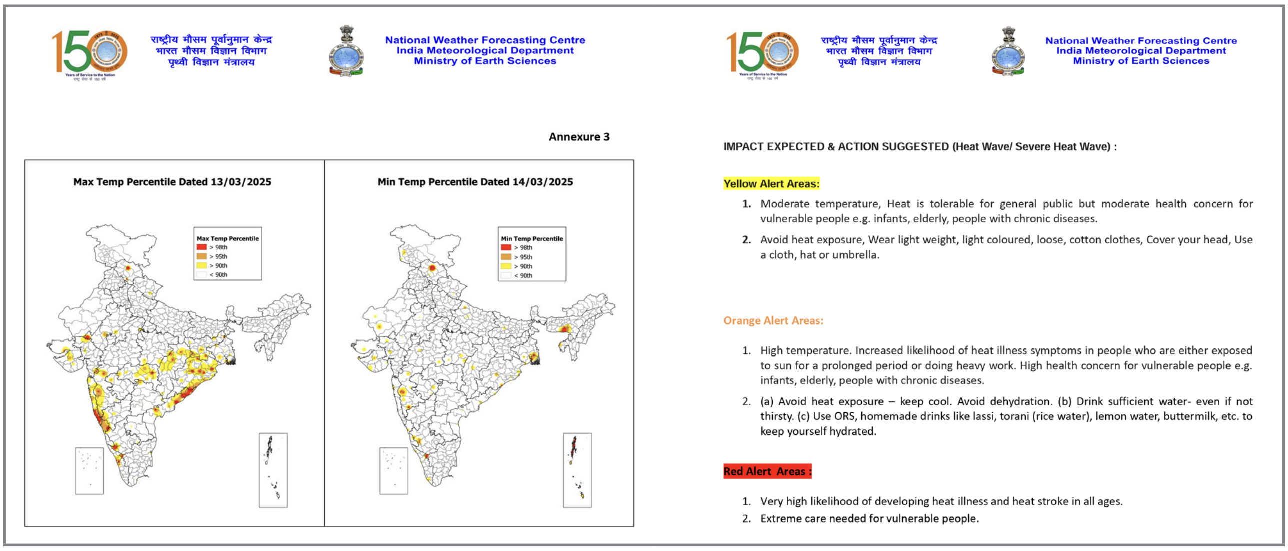
Based on our study's findings, we present some key recommendations for national, state, district, and city authorities. Most of our recommendations focus on using existing funding mechanisms more efficiently.

A. Move beyond a daytime temperature—based approach and incorporate warm nights, humidity, demographics, and health vulnerabilities into the second generation of HAPs

We reviewed the open-access HAPs of 15 states (as of November 2024) and found that only two states—Bihar and Andhra Pradesh—had conducted heat vulnerability mapping. To address this gap, we have developed free-to-use handbooks for every state and UT in India (Annexure 1). These feature district-specific heat risk maps and identify key risk drivers to strengthen decision-making and targeted resource allocation.

We also recommend that states pay attention to early warning systems that consider RH, percentile-based Tmax and Tmin exceedance, and sector-specific warnings. Since last few years, IMD has been providing these in its heatwave forecasts and bulletins, which regional meteorological centres disseminate to district and state nodal officers. Such early warning systems are essential to pre-empt outbreaks of heat-related illnesses and ensure last-mile connectivity.

Figure 20 A snapshot of an IMD forecast and advisory based on percentile thresholds dated March 15, 2025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भारत मौसम विज्ञान विभाग
पृथ्वी विज्ञान मंत्रालय

National Weather Forecasting Centre
India Meteorological Department
Ministry of Earth Sciences

Annexure 3

IMPACT EXPECTED & ACTION SUGGESTED (Heat Wave/ Severe Heat Wave) :

Yellow Alert Areas:

1. Moderate temperature, Heat is tolerable for general public but moderate health concern for vulnerable people e.g. infants, elderly, people with chronic diseases.
2. Avoid heat exposure, Wear light weight, light coloured, loose, cotton clothes, Cover your head, Use a cloth, hat or umbrella.

Orange Alert Areas:

1. High temperature. Increased likelihood of heat illness symptoms in people who are either exposed to sun for a prolonged period or doing heavy work. High health concern for vulnerable people e.g. infants, elderly, people with chronic diseases.
2. (a) Avoid heat exposure – keep cool. Avoid dehydration. (b) Drink sufficient water- even if not thirsty. (c) Use ORS, homemade drinks like lassi, torani (rice water), lemon water, buttermilk, etc. to keep yourself hydrated.

Red Alert Areas :

1. Very high likelihood of developing heat illness and heat stroke in all ages.
2. Extreme care needed for vulnerable people.

Source: IMD. 2025. Annual Climate Summary 2024. New Delhi: India Meteorological Department.

B. Operationalise state disaster mitigation funds

In 2020, the 15th Finance Commission recommended establishing the NDMF and SDMFs, which the Indian government subsequently accepted (Fifteenth Finance Commission 2020). In line with the *Disaster Management Act, 2005*, and the Commission's recommendations, the government framed guidelines for constituting and managing the NDMF and SDMFs.

In 2024, the Ministry of Home Affairs included heatwaves as disasters eligible for receiving project-based funding under the SDMF (Ministry of Home Affairs 2024). This fund was allocated INR 32,031 crore for FY 2021–26, with INR 7,046 crore earmarked for FY 2025–26 (2024). Of this, the MoHA stipulated that at least 10 per cent must be allocated for non-structural measures. Additionally, no more than 50 per cent of NDMF or SDMF funding could be used to mitigate risks created by a single hazard each year.

This includes creating cooling shelters (structural) and health-based early warning systems (non-structural). As per the SDMF guidelines, project proposals must be based on heat hazard, vulnerability, and risk mapping.

We recommend that SEOCs and SDMAs use our study's findings (Annexure 1) to identify district-level heat risk drivers and develop targeted heat risk mitigation proposals in alignment with the NDMA's framework.

C. Notify heatwaves as a state-specific disaster in states where more than half the districts fall in the high to very high heat risk category (see Table 6)

In addition to SDMF funding, notifying heatwaves as a state-specific disaster can unlock an additional 10 per cent of financing from the SDRF. The SDRF constitutes 80 per cent of the overall funds available for disaster risk management, but since heatwaves are not a nationally notified disaster, states cannot utilise the entire SDRF fund for responding to them. Notifying a heatwave at the state level can increase the total funding available for disaster management to 30 per cent. The areas these funds can be utilised include: i) ex-gratia payments for deceased persons; ii) compensation for crop loss and livestock deaths; and iii) capacity-building initiatives for first responders. High-risk states such as Maharashtra, Tamil Nadu, Andhra Pradesh and Madhya Pradesh, among others, have already notified heatwaves as a state-specific disaster, and others should follow suit.

D. Move away from absorbing heat-related losses and towards risk sharing through insurance mechanisms

We found that unlike rainfall—which shows high micro-climate variability—heat risk patterns in India are broadly similar within and across states. This presents disaster management agencies with an opportunity to move beyond reactive responses and explore risk-sharing mechanisms such as parametric heat insurance—a predefined, threshold-based insurance payout policy. Unlike regular insurance schemes that are based on indemnity, parametric insurance relies on a predetermined set of parameters. The moment these parameters are met, the insurance agency releases a payout.

Developing regional insurance models for districts or states with similar heat risks can enhance financial resilience and ensure timely compensation for heat-related losses. Such a mechanism was piloted in Nagaland, where the SDMA paid an annual premium of approximately INR 70 lakh for coverage of INR 5 crore. The trigger threshold was initially set between 290 and 350 mm of rainfall (Sirur 2024). Another recent example is from Ahmedabad, where parametric insurance against extreme heat was rolled out for SEWA members. This scheme benefitted nearly 46,000 women.

E. Establish a national repository of heat action plans

During our analysis, we found it challenging to quantify districts' adaptive capacity due to the lack of HAPs published in the public domain. We recommend setting up a centralised HAP database, hosted by the NDMA and managed and updated by SDMAs. This can improve HAP transparency, help track implementation progress, and facilitate continuous learning across cities, districts, and states. This repository can also help address design and implementation gaps in plans, making heat action planning more effective and data-driven.

Expanding built-up areas in Indian cities, especially tier II and III, are trapping heat and intensifying night-time temperatures.

Acronyms

AHP	analytic hierarchy process
CAGR	compound annual growth
CHDHN	consecutive hot days and nights
GDP	gross domestic product
DTR	diurnal temperature range
GIS	geographic information system
HAP	*heat action plan*
HHWS	heat health warning system
HI	heat index
HRI	heat risk index
ILO	International Labour Organization
IMD	India Meteorological Department
IMDAA	Indian Monsoon Data Assimilation and Analysis
IPCC	International Panel on Climate Change
IPCCAR	International Panel on Climate Change Assessment Report
LULC	land use and land cover
MGNREGA	*Mahatma Gandhi National Rural Employment Guarantee Scheme*
MoHFW	Ministry of Health and Family Welfare
NCD	non-communicable diseases
NCMRWF	National Centre for Medium Range Weather Forecasting
NDMA	National Disaster Management Authority
NDRF	National Disaster Response Force
NFHS	National Family Health Survey
NHA	National Health Authority
NGO	non-governmental organisation
NMM	*National Monsoon Mission*
OGDP	open government data platform
PMJAY	*Pradhan Mantri Jan Arogya Yojana*
RH	relative humidity
SDMA	state disaster management authority
SDMF	state disaster mitigation fund
SDRF	state disaster response force
SEOC	state emergency operations centre
SEWA	Self-Employed Women's Association
SHC	sub-health centre
SOI	Survey of India
UNFCCC	United Nations Framework Convention on Climate Change
UT	union territories
WHO	World Health Organization
WMO	World Meteorological Organization

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