RINOLYST

2025 HEATWAVES
ON HUMAN HEALTH

STRATEGIC PREPAREDNESS FOR HEATWAVES ON HUMAN HEALTH

Impacts on Human Health, Past Lessons, and Pathways to Resilience: Anticipating Heatwave Challenges in India: March to June 2025

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SciGlyph Exploration Private Limited, India

NetZero India Foundation

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HIGHLIGHTS

- Examines rising heatwave trends, health impacts, and regional vulnerability disparities.
- Explores Heat Index, WBGT, and biometeorological indicators for heat risk assessment.
- Provides city-specific HI forecasts until June 15, 2025, highlighting adaptation needs.
- Identifies research gaps and innovations for equitable heat resilience strategies.

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To the readers

India is experiencing an alarming escalation in extreme heat events, with record-breaking temperatures and prolonged heatwaves posing significant challenges to public health, infrastructure, and economic stability. In recent years, the country has witnessed some of its highest recorded temperatures, including 52.9°C in Mungeshpur, Delhi (May 29, 2024); 51°C in Phalodi, Rajasthan (May 19, 2016); 50.8°C in Churu, Rajasthan (May 25, 2019); 50.6°C in Ganganagar, Rajasthan (May 27, 2019); and 50.3°C in Sirsa, Haryana (May 28, 2024). With 2024 officially declared the hottest year on record, the risks associated with extreme heat have intensified. The World Meteorological Organization has projected a 66% likelihood that the annual global temperature will exceed 1.5°C above pre-industrial levels for at least one year between 2023 and 2027, with a 98% probability that this period will include the warmest year on record. These projections underscore the increasing likelihood of unpredictable and extreme temperature surges that could surpass current adaptation capacities.

This report provides city-specific Heat Index (HI) forecasts until June 15, 2025, offering a valuable resource for policymakers, urban planners, public health officials, educators, industry leaders, and communities. The report is structured to enhance understanding of heatwaves and their far-reaching impacts. It begins with an overview of heatwaves and their effects on human health, followed by an examination of the Heat Index as a critical tool for assessing heat stress. A comprehensive forecast of the HI across major Indian cities is presented, enabling stakeholders to anticipate and prepare for upcoming heat risks. However, given the limitations of the Heat Index, particularly its tendency to overestimate risk at extreme temperatures due to its assumptions of shaded environments and low wind speeds, this report also discusses the Wet Bulb Globe Temperature (WBGT), which provides a more accurate measure of heat stress by incorporating solar radiation, wind speed, and other environmental factors.

Beyond HI and WBGT, the report explores advanced assessment and monitoring strategies, integrating multiple heat stress indices, remote sensing technologies, and real-time meteorological data to improve predictive accuracy. The final sections outline key research questions addressing current gaps in heat-risk assessment and the necessity for enhanced modeling techniques to strengthen long-term climate resilience.

While conventional weather forecasts typically extend only seven to ten days, this report bridges a critical gap by offering an extended heat stress outlook through mid-June 2025. By equipping decision-makers with early insights into prolonged heat risks, it facilitates strategic planning across healthcare, labour regulations, education, and urban infrastructure. Strengthening early warning systems and implementing data-driven adaptation strategies will be essential to safeguarding both lives and livelihoods as India faces an increasingly volatile and extreme climate.

The final version of this study will be uploaded by late 2025 or early 2026 based on the precise observation of realistic data of heat wave 2025.

Significance of This Report

This report presents essential city-specific heat index forecasts until June 15, 2025, offering a valuable resource for policymakers, urban planners, public health officials, educators, industry leaders, and communities. By providing data-driven insights, it supports proactive decision-making and targeted interventions to mitigate the impacts of extreme heat, safeguard public health, and enhance societal resilience.

- **Enhanced Early Warning Systems:** By forecasting heat index trends, this report supports the development of more precise heatwave early warning systems, enabling timely interventions to mitigate health risks and infrastructure challenges.
- **Public Health and Emergency Preparedness:** Accurate heat index projections allow healthcare facilities, emergency responders, and public health authorities to anticipate and manage heat-related illnesses, reducing mortality and hospitalizations.
- **Community and Urban Resilience:** Local governments and municipal bodies can utilize these forecasts to implement targeted heat action plans, establish cooling shelters, and issue public advisories, safeguarding vulnerable populations.
- **Workforce and Occupational Safety:** Industries, construction sites, and labour-intensive sectors can leverage this data to adjust work schedules, enforce heat safety protocols, and minimize health risks for outdoor workers.
- **Education Sector Adaptation:** Schools, colleges, and universities can use the forecasts to assess heat risks, modify academic schedules, and implement protective measures to ensure safe learning environments for students and staff.

- **Energy and Infrastructure Management:** Understanding peak heat stress periods aids in electricity demand management, allowing utility providers to optimize power distribution and prevent grid failures during extreme heat events.
- **Agriculture and Food Security:** Forecasted heat index trends provide essential information for farmers and agricultural planners to mitigate heat-induced crop stress, optimize irrigation strategies, and protect livestock health.
- **Transportation and Public Services:** City planners and transportation authorities can take precautionary measures to prevent heat-related disruptions, ensuring the safety and efficiency of public transport and essential services.
- **Disaster Risk Reduction and Climate Adaptation:** Policymakers can integrate heatwave projections into broader climate resilience strategies, strengthening long-term preparedness against rising temperatures and extreme weather events.

Heatwaves

Heatwaves, characterized by significant temperature increases above regional norms, have transformed from a seasonal phenomenon in India into a persistent crisis with profound implications for public health, economic productivity, urban infrastructure, and environmental sustainability. Historically confined to the pre-monsoon month of May, these events have grown in frequency, intensity, and duration, a trend exacerbated by climate change linked to human-induced emissions [1,2].

Between 1901 and 2018, India's average annual temperature increased by approximately 0.7°C, a rise that contributed to over 24,000 heatwave-related deaths between 1992 and 2015 [3,4]. Certain regions including, West Rajasthan, North Madhya Pradesh/Southwest Uttar Pradesh, and East Maharashtra recorded the highest maximum temperatures from 1951 to 2015, while northern, northeastern, and southeastern zones exhibited heightened vulnerability due to intricate atmospheric circulation dynamics [5,6]. A striking example occurred in 2010, when Ahmedabad endured an extreme heatwave resulting in over 1,300 fatalities [7]. On a global scale, temperatures are benchmarked against the pre-industrial (1850–1900) average, with the mean reaching 1.15°C above this baseline by 2022 [8, 9].

Over the past century (1906–2005), global surface air temperatures have risen by approximately 0.74°C, with land temperatures increasing at a significantly higher rate than the global average [10]. In India, the annual mean land surface air temperature has exhibited a pronounced warming trend of 0.62°C per 100 years (1901–2003), largely driven by an increase in maximum temperatures. This rise has been mainly amplified by rapid industrialization and urban expansion, which have contributed to localized heating effects and broader climatic shifts [11]. Urbanization has significantly intensified regional warming, as evidenced by a study on India's National Capital Region (NCR) from 1972 to 2014 [12]. A 17-fold expansion in built-up areas led to land surface temperature increases of up to 5°C and near-surface air temperature rises of 4°C. Nighttime temperatures have also climbed by 1.5°C, while weaker winds and declining humidity have reduced atmospheric ventilation, worsening pollution levels. Additionally, urban land-use changes alone have contributed to an estimated 1.5°C rise in surface temperatures [12,13].

From 2000 to 2012, heatwaves in Northwest India elevated total mortality by 18.1%, with Jaipur experiencing a peak increase of 29.9%, though variations in duration, intensity, and timing exerted minimal influence on mortality risk [14]. Since 2015, global temperatures have consistently exceeded, reached 1°C above the pre-industrial era for the first time ever, underscoring the urgency of limiting warming to below 2°C, and preferably 1.5°C, as set forth in the Paris Agreement [15,16]. This rise in temperature during years 2015-16 was driven by a combination of anthropogenic climate change and a strong El Niño [17]. In 2021, heat stress affected 68 million people worldwide, with projections indicating that a 2°C rise could expose one billion individuals to extreme conditions, emphasizing the critical importance of the Paris Agreement's 1.5°C–2°C targets [16]. By 2022, global temperatures had already risen to 1.15°C above pre-industrial levels [8]. The year 2022 underscored India's increasing susceptibility, as temperatures exceeded 40°C in March across western and central regions, triggering severe heatwaves [18]. However, the most prolonged exceedance occurred from late 2023 into early 2024, with sustained monthly temperature anomalies above 1.5°C, culminating in the first full 12-month period (February 2023 to January 2024), intensified by a potent El Niño, averaging 1.52°C above the 1850-1900 baseline [19,20,8]. By 2024, India recorded an unprecedented 536 heatwave days (the highest since 2010) with Rajasthan and Delhi surpassing 50°C, while global temperatures briefly breached 1.5°C, marking a decade of exceptional warming [21,19,22,23,24]. India's highest recorded temperature was 52.9°C in Mungeshpur, Delhi, on May 29, 2024, followed by 51°C in Phalodi, Rajasthan, on May 19, 2016; 50.8°C in Churu, Rajasthan, on May 25, 2019; 50.6°C in Ganganagar, Rajasthan, on May 27, 2019; and 50.3°C in Sirsa, Haryana, on May 28, 2024. Declared the hottest year on record, 2024 highlighted the pressing need for decisive climate action [25,26,23]. According to the World Meteorological Organization, there is now a 66% likelihood that the annual average near-surface global temperature will exceed 1.5°C above pre-industrial levels for at least one year between 2023 and 2027, and a 98% likelihood that this period will include the warmest year on record [8].

By early 2025, the crisis had intensified further. In February, Mumbai, typically tempered by coastal influences, reached an extraordinary 38.7°C, 5.9°C above its long-term average, due to insufficient winter rainfall (January-February) [27,28,22,29,30]. The India Meteorological Department (IMD) projected above-normal maximum temperatures and increased heatwave days for March 2025 across most of India, excluding the southernmost Peninsular regions, Northeast, extreme north, and parts of southwestern and southern Peninsular India [31]. Forecasts (for the 3rd week of March 2025) also anticipated isolated to scattered light to moderate rainfall with thunderstorms and gusty winds in areas such as Sub-Himalayan West Bengal, Bihar, and Odisha, alongside isolated hailstorms in Jharkhand and Gangetic West Bengal [32]. Temperature shifts included a 2-3°C rise in Northwest India, a 2-4°C decline in Central India, and a 3-5°C drop in East India over mid-March, with recorded highs of 40-42°C in Odisha and Andhra Pradesh, peaking at 40.8°C in Kurnool on March 18 [33].

The ramifications of heatwaves are extensive and interconnected. Energy demand escalates by 8–10% during extreme heat, water resources are strained by evaporation and over-extraction, and agricultural yields decline by 10–15%, jeopardizing food security and rural livelihoods. Urban centres, worsened by the heat island effect, endure unrelenting nighttime heat, could lead to a reduced outdoor working capacity by 15%, reduce quality of life up to 480 – 600 million, potentially reducing India's GDP by 2.8% by 2050 [34,35]. Projections indicate a temperature increase of up to 5°C by 2100 under current emissions trajectories, though some estimates suggest a range of 1.2°C to 3.5°C with a possible decline by 2050 [3,36]. Coastal areas in India may encounter wet-bulb temperatures of 35°C by 2050, posing risks to 90% of India's population [37,38,39,40]. Human activities have doubled the probability of severe heat events in central and mid-southern India, with a potential tenfold increase in severity, while simultaneous day-and-night (frequency of 3-day: 3-day concurrent hot day and hot night) heat events could rise twelvefold under high warming scenarios [41,42,43,36].

Efforts to mitigate this crisis provide a viable framework for response. Ahmedabad's Heat Action Plan, initiated in 2013, effectively reduced heat-related mortality through early warning systems, cooling centres, and public education [44]. Building on this model, India is advancing nationwide preparations for extreme heat. Yet, addressing these complex challenges demands a holistic approach, integrating advanced forecasting, renewable energy adoption, sustainable water management, and urban greening. Cities such as Jaipur, Delhi, Ahmedabad, Mumbai, and Kolkata confront distinct challenges, from Rajasthan's arid heat to the urban pressures of major metropolises, necessitating customized solutions.

Heatwaves on Human Health

Heatwaves, defined by the World Meteorological Organization as prolonged periods of abnormally high temperatures often paired with high humidity, represent a critical and growing threat to human health that is becoming increasingly evident worldwide. In the context of global warming, even a modest rise in average ambient temperature has been linked to a marked increase in the frequency, intensity, and duration of these extreme events. In 2023, the global impact of rising temperatures was nothing short of staggering [45]. People lost about 6% of their sleep, 5% more than in the period from 1986 to 2005 globally, and on average faced 50 additional days of health-threatening heat. Work productivity took a massive hit as well, with a record 512 billion potential work hours lost, nearly 50% above the 1990–1999 average. Moreover, individuals were exposed to approximately 27.7% more hours each year during which ambient heat posed at least moderate stress during light outdoor activities compared to the 1990s. Alarmingly, vulnerable groups like infants and adults over 65 experienced an average of 13.8 heatwave days per person in 2023. These figures clearly illustrate how climate change is not just an abstract threat but a daily reality affecting sleep, health, and economic productivity worldwide [45]. Heatwaves, especially when combined with high humidity, pose a severe risk to human health by impairing the body's ability to regulate temperature, leading to increased mortality and morbidity [46]. Even at moderate air temperatures, excessive humidity intensifies heat stress, making wet-bulb temperature (Tw), Heat Index (HI), and Wet-Bulb Globe Temperature (WBGT) critical indicators for assessing human vulnerability. Studies show that Tw exceeding 29–31°C has led to mass fatalities, while physical labor becomes life-threatening at Tw above 35°C, as evaporative cooling fails [39, 47, 48]. Historical heatwaves, such as those in Europe (2003), Russia (2010) and South Asia (2015), have resulted in thousands of deaths, with recent trends showing more frequent exceedances of critical heat stress thresholds [46,49,50,51]. Global projections indicate that under continued warming, densely populated regions could experience humid heatwaves with apparent temperatures surpassing 55°C, increasing health risks for outdoor workers, the elderly, and low-income urban populations. Integrating biometeorological indices, improving heat-health warning systems, and strengthening adaptive measures are crucial for mitigating these growing threats.

For instance, between 2016 and 2024, India experienced extreme daily temperatures ranging from 50°C to 53°C (mentioned earlier) across various regions, alongside an unprecedented 536 heatwave days in 2024, the highest in recent history [21,24]. These extreme conditions impose severe physiological stress, as the human body depends on precise thermoregulatory mechanisms to maintain a stable core temperature within a safe range.

The human body typically maintains a temperature between ~36.4°C and ~37.2°C [52]. Prolonged exposure to extreme heat, whether outdoors or indoors, can lead to heat stress, triggering a range of heat-related illnesses. These conditions vary in severity, from mild issues like heat rash, swelling (heat edema), and muscle cramps to more serious complications such as heat tetany, fainting (heat syncope), heat exhaustion, and potentially fatal heat stroke. Additionally, heat stress can worsen chronic conditions, including cardiovascular, respiratory, and kidney diseases [53]. When the body is exposed to sustained high temperatures, it may first exhibit mild symptoms such as skin irritations (prickly heat), heat cramps, and heat edema. As the stress intensifies, these symptoms can escalate into heat syncope, a temporary fainting spell due to a drop in blood pressure, before progressing to more serious conditions like heat exhaustion, characterized by dehydration and cardiovascular strain. The most severe and life-threatening response is heat-stroke, where core body temperature exceeds 40°C, often leading to hyperthermia, central nervous system dysfunction, and multi-organ failure if not promptly treated [54,55]. Alongside these acute conditions, heatwaves also disrupt normal sleep architecture, particularly reducing the duration and quality of deep N3 (formerly slow-wave sleep) and REM (Rapid eye movements) sleeps, which is vital for cognitive function, emotional regulation, and overall recovery [54]. This sleep disruption not only hampers immediate cognitive performance but also increases long-term risks of cardiovascular and metabolic disorders [56,57,58,59].

Key aspects of the impact of heatwaves on human health, ranked from the most severe to less critical, include:

- **Heat Stroke:** The most dangerous outcome, where a rapid rise in core temperature overwhelms the body's cooling systems, often leading to multi-organ failure and death.
- **Heat Exhaustion:** A serious condition marked by dehydration, dizziness, and weakness that, if not managed, can progress to heat stroke.

- **Heat Syncope:** Fainting spells resulting from a temporary drop in blood pressure during sudden heat exposure, serving as an early warning sign.
- **Heat Cramps, Heat Edema, and Prickly Heat:** Less severe yet still significant conditions that cause discomfort and reduced quality of life, particularly among the vulnerable.
- **Secondary Effects:** Chronic cardiovascular strain, disrupted sleep leading to cognitive and emotional impairment, and heightened mental health issues such as anxiety and depression.

Globally, nations such as the United States, Japan, and several European countries have developed and implemented sophisticated monitoring techniques, ranging from continuous core temperature tracking and advanced polysomnography to the use of indices like the Heat Wave Magnitude (HWM) Index to accurately predict and manage the health impacts of heatwaves [60,61]. These countries have also introduced comprehensive Heat Action Plans (HAPs) that integrate early warning systems, public education initiatives, urban cooling strategies like reflective roofing and increased green cover, and structured heat acclimation protocols to mitigate adverse health outcomes. Despite these advances, significant challenges remain, including the integration of meteorological, physiological, and socioeconomic data to form a holistic risk profile, as well as ensuring that vulnerable populations, such as the elderly, children, and low-income communities, receive equitable access to necessary adaptive measures.

Lessons learned from global initiatives highlight the importance of a multidisciplinary approach to tackle this public health emergency. Effective monitoring tools, such as real-time data analytics, wearable health devices for continuous body temperature assessment, and detailed sleep studies, are critical for early detection and intervention. Yet, research gaps persist, especially regarding long-term acclimation processes and the precise interplay between sleep disruption and heat exposure, which must be addressed to further refine predictive models and develop more targeted public health strategies.

The comprehensive body of research unequivocally confirms that heatwaves are not merely an occasional inconvenience but a severe, multifaceted public health crisis. The increasing intensity and duration of these events, driven by global climate change and exacerbated by urbanization, call for urgent, coordinated action across multiple sectors to safeguard human health, enhance resilience, and ensure a sustainable future.

Heat Exhaustion vs. Heat Stroke

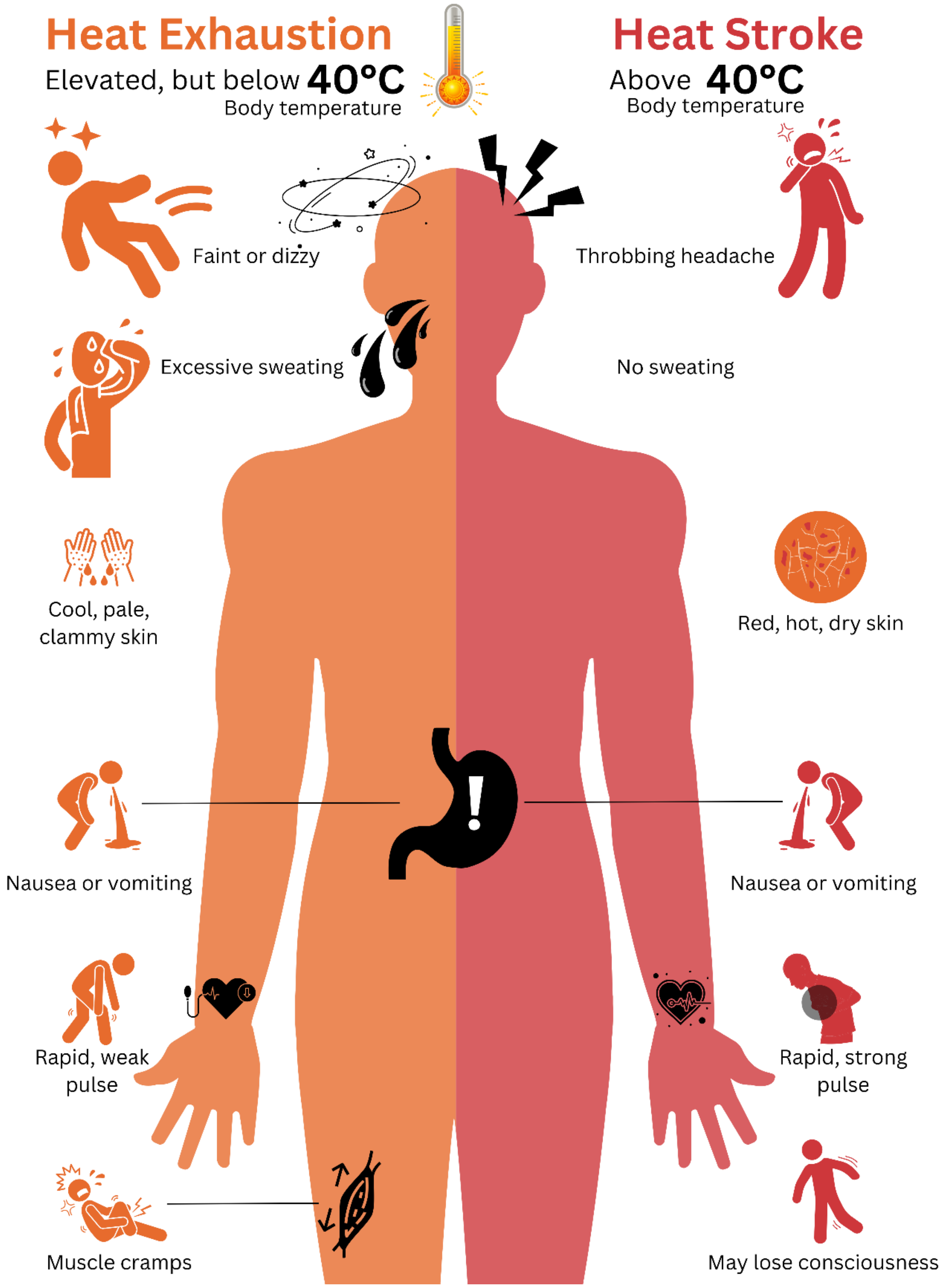


Figure 1. Signs of heat illness: heat exhaustion vs heat stroke (modified) [62].

Heat exhaustion is a milder form of heat-related illness where the body can still regulate its temperature, whereas heat stroke is a medical emergency where the body loses its ability to cool itself, leading to dangerously high temperatures. Recognizing the difference is crucial to prevent serious health risks.

Table 1. Understanding of heat exhaustion and heat stroke [53,63,64,65].

Aspect	Heat Exhaustion	Heat Stroke
What it is	Body overheats but can still regulate temperature.	Body loses the ability to regulate temperature.
Symptoms	Dizziness, headache, nausea, weakness, muscle cramps, and fatigue.	Confusion, altered mental status, seizures, coma.
Core Temperature	Elevated, but below 104°F (40°C).	Above 104°F (40°C).
Treatment	Move to a cooler place, loosen clothing, apply cool compresses, and drink fluids.	Immediate medical attention, rapid cooling (e.g., cold water immersion).
Progression	Can lead to heat stroke if untreated.	Life-threatening, may cause organ damage or death if untreated.

Impact

In India, heatwaves typically occur from March to July, with most fatalities and damages recorded between May and July. Heatwave related extreme conditions pose a growing public health risk, causing minor issues like heat rash and cramps, as well as severe illnesses such as heat exhaustion and heatstroke, the most dangerous heat-related condition. Heatwaves in India have emerged as a serious public health crisis, with their frequency, intensity, and duration increasing due to climate change and the urban heat island (UHI) effect.

The Lancet (Health and Heat, Lancet Countdown on Health and Climate Change data explorer) has explored, estimated, and forecasted the impact of heat on health worldwide [66]. According to the available data, India is experiencing a sharp rise in heatwave-related health risks, with vulnerable populations, such as infants and older adults, facing an increasing number of extreme heat days. Infants now endure 2.5 more heatwave days per year, while older adults experience 3.1 additional days compared to the 1986–2005 period. By 2041–2060, older adults could face 31.63 extra heatwave days annually under a 3.7°C warming scenario. Rising temperatures are also reducing safe outdoor activity, with 7.33 hours per day of moderate heat stress risk in 2023, up from 6.39 hours in 1990, a figure that could rise by 378.77 additional annual hours by mid-century. The economic toll is severe, with India losing 181.6 billion labour hours in 2023 across key economic sectors, up from 123.9 billion in 1991–2000. Agriculture remains the hardest hit, with cumulative lost labour hours reaching 323 billion, followed by construction (96.4 billion), manufacturing (37.9 billion), and services (55.1 billion) in 2023 alone. These losses could rise by an additional 9.76% annually by mid-century under a 3.7°C warming scenario. Heat-related mortality is also surging, with over-65 mortality rising 89.1% since the 1990s, compared to an estimated 70.2% increase without climate/temperature change. If global temperatures rise by 3.7°C by 2100, India could witness 259,658 additional annual heat-related deaths among older adults by mid-century. These alarming trends underscore the urgent need for climate adaptation strategies, improved labour protections, and public health interventions to mitigate the escalating health impacts of heatwaves.

A comprehensive analysis of heatwaves from 1978 to 2014 found that India experienced 660 recorded heatwave events, resulting in 12,273 fatalities, an average of 332 deaths per year [24]. Alarmingly, over 80% of these deaths were concentrated in just five states: Andhra Pradesh (42%), Rajasthan (17%), Odisha (10%), Uttar Pradesh (7%), and Bihar (7%). Andhra Pradesh alone saw an average of 104 deaths per heatwave event. Most of these fatal incidents occurred in the pre-monsoon months of April, May, and June, with men being disproportionately affected due to their higher participation in outdoor labour.

In recent years, the situation has worsened. In the summer of 2024, India experienced a total of 536 heatwave days, the highest in 14 years, following 578 days in 2010. June, 2024 alone saw 181 heatwave days, surpassing the previous high of 177 days recorded in 2010. The northwestern region endured its warmest June since 1901 [21]. The extreme heat led to over 40,000 suspected heatstroke cases and more than 100 heat-related deaths, highlighting the severity of this year's prolonged and intense heatwave [67]. However, independent data from HeatWatch suggests the toll may be over 600-700 [68,69]. The impacts have been particularly severe in Andhra Pradesh and Telangana, where nearly 3,600 people died from heatstroke between 2012 and 2022 [68]. Hyderabad experienced record-breaking temperatures of 47.2°C in May 2024, prompting red alerts in 14 districts as temperatures soared past 45°C.

Jeroen de Bont and colleagues estimated that heatwaves contribute to an average of 1,116 additional deaths per year across 10 Indian cities, highlighting a significant public health concern, especially if similar trends are seen nationwide [70]. While previous studies in India have primarily examined how rising temperatures affect mortality, research specifically focused on heatwaves remains limited [71]. Most studies have looked at individual cities, such as Ahmedabad's extreme 2010 heatwave, where temperatures soared to 46.8°C, leading to over 1,300 deaths, with 800 occurring in just one week [7]. de Bont's study also identifies Ahmedabad as one of the most affected cities, with around 300 heatwave-related deaths each year [70]. Similar trends were observed in Varanasi [72]. Additionally, research has established a clear link between heatwaves and increased mortality in northwest India [14].

Beyond fatalities, heatwaves disproportionately impact vulnerable groups, particularly gig and platform workers such as cab drivers, auto-rickshaw drivers, and delivery workers. With limited access to water, shade, and restrooms, they face significant health risks, including dehydration, heat exhaustion, kidney failure, and heat stroke. Heatwave-related deaths surpass those from avalanches, extreme cold, cyclones, earthquakes, epidemics, floods, and other natural disasters. Study highlights regional variations in heatstroke fatalities and emphasizes that such deaths occur annually, with numbers expected to rise due to increasing temperatures [73]. This underscores the urgent need for region-specific interventions to mitigate heatwave-related mortality.

These alarming trends highlight the urgent need for enhanced disaster management strategies, targeted public health interventions, and further research to address the environmental factors fueling these extreme events. Immediate action is necessary to protect lives, especially among high-risk populations, as heatwaves continue to intensify across the country.

Table 2. Numbers of deaths due to heatwaves either reported in news medias or estimated in literatures/journal articles.

Spells	State	Fatalities	References
1970-2019	India	17362	[36]
1978-1999	Rajasthan	1625	[74]
6 – 16 May 1988	Rajasthan	337	[24]
1992 - 2015	India	22000	[75]
		24000	[36]
June 1995	India	350+	[76]
1995		1677	[77]
1 – 31 May 1998	Andhra Pradesh	355	[24]
20 – 30 May 1998	Odisha	340	[24]
May–June 1998	India	2500	[78]
2001-2005	Uttar Pradesh	606	[36]
9 – 15 May 2002	Andhra Pradesh	600	[24]
March-mid May 2002	Southern India	1030	[79]
15 May – 30 June 2003	Andhra Pradesh	1300	[24]
2003		~3000	[70,80]
2005	Odisha	236	[81]
1 - 31May 2010	Ahmedabad	~1350	[7]
2011-2015	Uttar Pradesh	981	[36]
May - 3 June 2015	India	2500	[82]
	Andhra Pradesh	1020+	[83]
	Telangana	340+	[83]
April – May 2016	India	1100+	[84]
2018	Uttar Pradesh	176	[85]
May-June 2019	Bihar	184	[86]
April–June 2023	India	111	[87]
As of 30th June 2023	Kerala	120	[85]
June 2023	Bhojpur (Bihar)	50	[88]
15-18 June 2023	Ballia (Uttar Pradesh)	68	[75]
As of 3rd June 2024	Odisha	147	[89]
2024	Delhi	60	[90]
As of 20th June 2024	India	209 (448)	[91]
March–May 2024	India	507	[92]
March and June 2024	India	733	[68]

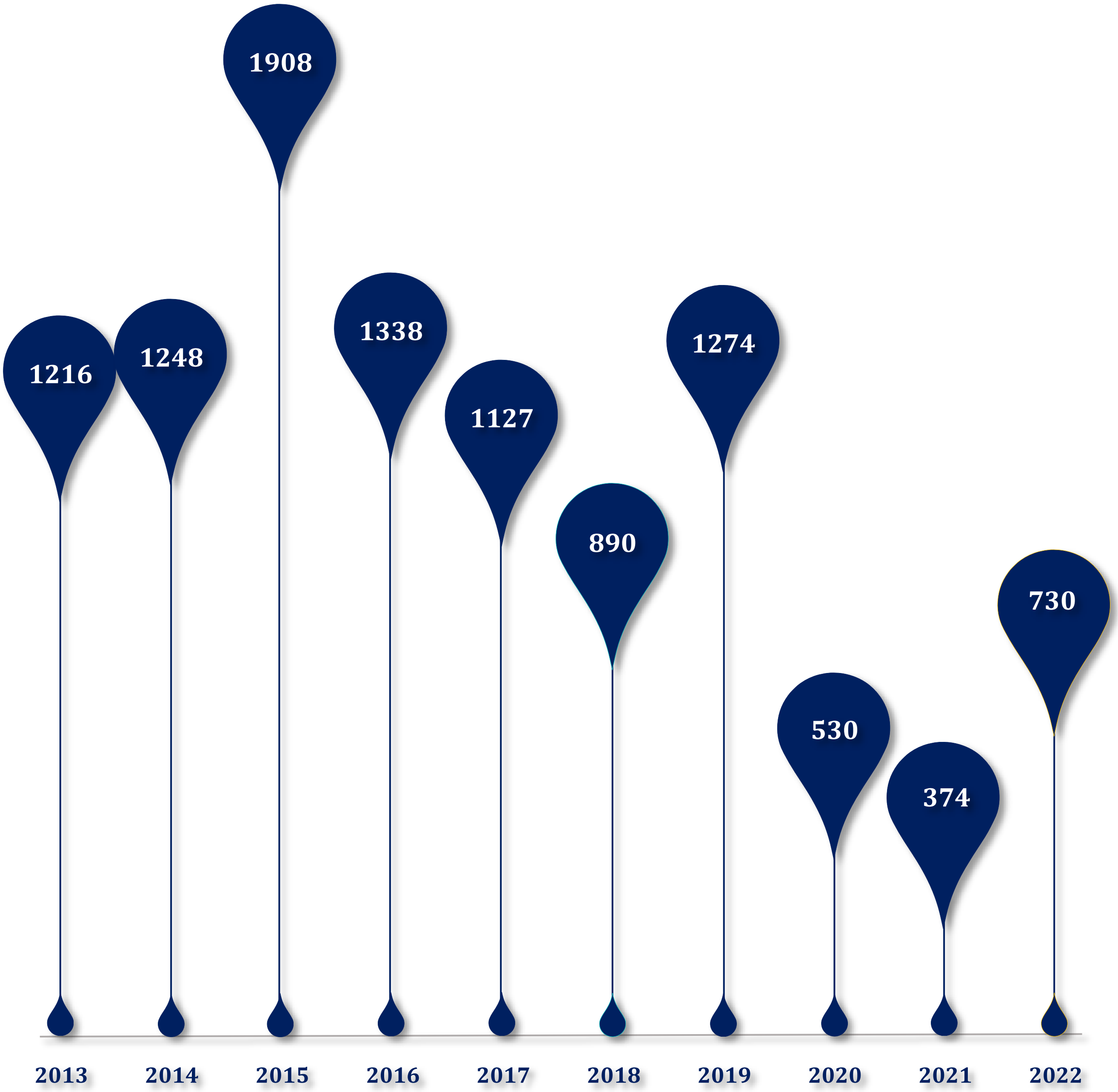


Figure 2. Officially reported deaths due to heatwaves in India [93].

From the above Table 2 and the Figure 2, it has been clear that the heatwave deaths are likely underreported in official figures, as causes can be misclassified due to a lack of biometeorological evidence. Accurately tracking heatwave-related deaths in India remains a significant challenge due to inconsistencies in reporting, variations in classification criteria, and logistical difficulties in data collection. A stark example of this issue emerged in June 2023 in Bihar's Bhojpur district, where India News reported that Ara Sadar Hospital alone recorded 50 heat-related deaths in just five days, including 25 fatalities in a single day [88]. Yet, the India Meteorological Department (IMD) in its official report recorded only 12 heatwave deaths for the entire state that year [94]. This highlights the difficulties in verifying and standardizing heat-related mortality across different levels of administration, a problem that persists nationwide.

Discrepancies in reported heatwave deaths are evident across multiple sources. In 2023, IMD itself presented conflicting figures, listing 181 heatwave deaths in its Disastrous Weather Events - 2023 monograph but only 119 deaths in its Annual Report 2023 [94,95]. Another official report under the National Programme on Climate Change & Human Health cited 189 fatalities, while the Union Ministry of Health and Family Welfare reported 264 deaths based on state submissions to the Lok Sabha [85,96]. Kerala alone accounted for 120 of these deaths; meanwhile, media reports suggested even higher numbers, particularly in Uttar Pradesh, where nearly 150 deaths were attributed to heatwaves in just two districts, though state authorities contested these figures [85].

A similar pattern of reporting inconsistencies continued in 2024. By June 20, the Union Health Ministry confirmed 143 heatstroke deaths, with Uttar Pradesh (35) and Delhi (21) recording the highest tolls. However, a compilation by The Economic Times, based on state-reported figures, indicated 209 confirmed deaths and an additional 239 suspected cases, bringing the total to 448 fatalities [91]. As investigations into suspected cases were still ongoing, the final toll remained uncertain. Despite inconsistencies in fatality figures, the broader health impact of extreme heat in 2024 has been severe. Another report highlights that suspected heatstroke cases surged to 48,156, with suspected and confirmed heatstroke deaths standing at 269 and 161, respectively [96]. While confirmed fatalities appeared lower than in previous years, emergency visits and cardiovascular-related deaths increased significantly, reflecting the immense strain on public health. These trends must be interpreted with caution, considering changes in reporting practices and expanding exposure to extreme heat. Variations in reported heatwave-related fatalities have also appeared in peer-reviewed scientific literature. For instance, one study cites 17,362 deaths in India over a longer period (1970–2019), while the same source reports 24,000 deaths within a shorter timeframe (1992–2015) [36]. Such inconsistencies highlight the challenges in data accuracy, which can impact the reliability of simulations and assessments used for policy and preparedness strategies.

The growing frequency and intensity of heatwaves only compound these issues. In 2024, India experienced 54 days of heatwave conditions between March and May, nearly double the 28 days recorded in 2023, leading to at least 507 reported deaths during this period alone [92]. When additional fatalities from February and June are considered, the total heatwave-related death toll exceeded 730. Vulnerable groups, such as outdoor labourers and farmers in North India, endured prolonged exposure to extreme temperatures with limited access to relief, exacerbating health risks [68,92]. However, one of the primary reasons for discrepancies in heatwave death counts is the difficulty in directly attributing fatalities to extreme heat. India's vast geography, dense population, and regional variations in death classification make standardized reporting difficult. National guidelines exist for identifying, categorizing, and conducting autopsy of heat-related deaths, but their implementation remains inconsistent and required necessary training/sensitization [97,98]. Many heatwave victims suffer from pre-existing conditions such as cardiovascular disease, which may obscure the role of extreme heat in their deaths. In rural areas with limited healthcare infrastructure, diagnosing and documenting heat-related fatalities is even more challenging, further contributing to underreporting.

The inconsistencies in heatwave mortality data underscore the urgent need for more reliable tracking mechanisms. Without accurate reporting, policymakers and health officials may struggle to implement effective interventions. Strengthening mortality surveillance, improving coordination between local and national agencies, and expanding access to healthcare in heat-prone regions are critical steps in mitigating the worsening impacts of extreme heat. As heatwaves become more frequent and severe, bridging these data gaps is essential to ensuring better preparedness and protecting vulnerable communities.

Understanding the Heat Index

The heat index (HI), or apparent temperature, quantifies the combined impact of air temperature and relative humidity on human perception of heat, reflecting how environmental conditions hinder the body's ability to cool through sweat evaporation. Developed by the U.S. National Weather Service (NWS) using the Rothfusz equation, HI calculations integrate temperature (°F) and humidity (%) to model heat stress [99]. For example, a 35°C (95°F) day with 70% humidity in Mumbai can feel like ~50°C (122°F), as moisture-laden air drastically slows sweat evaporation, the body's primary cooling mechanism.

The heat index chart (Figure 3), also known as the apparent temperature chart, estimates how hot it feels to the human body by accounting for both air temperature and relative humidity, making it a crucial tool for assessing the risk of heat-related illnesses such as heat exhaustion and heatstroke. By identifying the intersection of temperature and humidity values, the chart provides a color-coded risk assessment, though factors like direct sunlight, wind conditions, and physical activity can further intensify heat stress.

HEAT INDEX °F (°C)													
The heat index is an accurate measure of how hot it really feels when the affects of humidity are added to high temperature.													
	RELATIVE HUMIDITY (%)												
Temp.	40	45	50	55	60	65	70	75	80	85	90	95	100
110 (47)	136 (58)												
108 (43)	130 (54)	137 (58)											
106 (41)	124 (51)	130 (54)	137 (58)										
104 (40)	119 (48)	124 (51)	131 (55)	137 (58)									
102 (39)	114 (46)	119 (48)	124 (51)	130 (54)	137 (58)								
100 (38)	109 (43)	114 (46)	118 (48)	124 (51)	129 (54)	136 (58)							
98 (37)	105 (41)	109 (43)	113 (45)	117 (47)	123 (51)	128 (53)	134 (57)						
96 (36)	101 (38)	104 (40)	108 (42)	112 (44)	116 (47)	121 (49)	126 (52)	132 (56)					
94 (34)	97 (36)	100 (38)	103 (39)	106 (41)	110 (43)	114 (46)	119 (48)	124 (51)	129 (54)	135 (57)			
92 (33)	94 (34)	96 (36)	99 (37)	101 (38)	105 (41)	108 (42)	112 (44)	116 (47)	121 (49)	126 (52)	131 (55)		
90 (32)	91 (33)	93 (34)	95 (35)	97 (36)	100 (38)	103 (39)	106 (41)	109 (43)	113 (45)	117 (47)	122 (50)	127 (53)	132 (56)
88 (31)	88 (31)	89 (32)	91 (33)	93 (34)	95 (35)	98 (37)	100 (38)	103 (39)	106 (41)	110 (43)	113 (45)	117 (47)	121 (49)
86 (30)	85 (29)	87 (31)	88 (31)	89 (32)	91 (33)	93 (34)	95 (35)	97 (36)	100 (38)	102 (39)	105 (41)	108 (42)	112 (44)
84 (29)	83 (28)	84 (29)	85 (29)	86 (30)	88 (31)	89 (32)	90 (32)	92 (33)	94 (34)	96 (36)	98 (37)	100 (38)	103 (39)
82 (28)	81 (27)	82 (28)	83 (28)	84 (29)	84 (29)	85 (29)	86 (30)	88 (31)	89 (32)	90 (32)	91 (33)	93 (34)	95 (35)
80 (27)	80 (27)	80 (27)	81 (27)	81 (27)	82 (28)	82 (28)	83 (28)	84 (29)	84 (29)	85 (29)	86 (30)	86 (30)	87 (31)

Figure 3. Heat Index (HI) chart [100].

Table 3. Health and Societal Implications [100].

Category	Heat Index	Possible heat disorders for people in high-risk groups
Extreme Danger	130°F or higher (54°C or higher)	Heat stroke or sunstroke likely.
Danger	105 - 129°F (41 - 54°C)	Sunstroke, muscle cramps, and/or heat exhaustion likely. Heatstroke possible with prolonged exposure and/or physical activity.
Extreme Caution	90 - 105°F (32 - 41°C)	Sunstroke, muscle cramps, and/or heat exhaustion possible with prolonged exposure and/or physical activity.
Caution	80 - 90°F (27 - 32°C)	Fatigue possible with prolonged exposure and/or physical activity.

Table 4. Adjusting work-rest schedules [101].

Actions and Impact Prevention	
Effects	**Precautionary Actions**
Working or exercising in direct sunlight will stress your body after 15 minutes.	**Take at least 45 minutes of breaks each hour if working or exercising in direct sunlight.**
Working or exercising in direct sunlight will stress your body after 20 minutes.	Take at least 40 minutes of breaks each hour if working or exercising in direct sunlight.
Working or exercising in direct sunlight will stress your body after 30 minutes.	Take at least 30 minutes of breaks each hour if working or exercising in direct sunlight.
Working or exercising in direct sunlight will stress your body after 45 minutes.	Take at least 15 minutes of breaks each hour if working or exercising in direct sunlight.

Vulnerable groups: children, the elderly, and those with chronic illnesses, face heightened risks due to inefficient thermoregulation. Proactive measures, such as Ahmedabad's Heat Action Plan (activating cooling stations at HI ≥45°C), underscore the index's role in policy. It should be noted that, full sunlight can elevate HI by up to 8°C, exacerbating dangers. Also, strong winds, particularly with very hot, dry air, can be extremely hazardous as the wind adds heat to the body.

Methodology and Regional Nuances

The HI is calculated using the Rothfusz regression equation developed and described in a 1990 National Weather Service (NWS) Technical Attachment (SR 90-23) [99].

The regression equation of Rothfusz is,

$$HI = -42.379 + 2.04901523 \times T + 10.14333127 \times RH - 0.22475541 \times T \times RH - 0.00683783 \times T \times T - 0.05481717 \times RH \times RH + 0.00122874 \times T \times T \times RH + 0.00085282 \times T \times RH \times RH - 0.00000199 \times T \times T \times RH \times RH$$

where T is temperature in degrees F and RH is relative humidity in percent. HI is the heat index expressed as an apparent temperature in degrees F.

In case of low humidity (<13%): Reduces HI for dry, hot winds; if the RH < 13% and the temperature is between 80 - 112°F, then the following adjustment is subtracted from HI:

$$ADJUSTMENT = [(13-RH)/4] \times SQRT\{[17-ABS(T-95)]/17\}$$

where ABS and SQRT are the absolute value and square root functions, respectively.

In case of high humidity (>85%): Increases HI in stagnant, moist air; if the RH > 85% and the temperature is between 80 and 87°F, then the following adjustment is added to HI:

$$ADJUSTMENT = [(RH-85)/10] \times [(87-T)/5]$$

Note: The Rothfusz regression is not appropriate when conditions of temperature and humidity warrant a heat index value below about 80°F. In such cases, a simpler formula is applied to calculate values consistent with Steadman's results:

$$HI = 0.5 \times \{T + 61.0 + [(T-68.0) \times 1.2] + (RH \times 0.094)\}$$

In practice, the simple formula is computed first and the result averaged with the temperature. If this heat index value is 80°F or higher, the full regression equation along with any adjustment as described above is applied.

Regional adaptations highlight disparities:

- **Coastal cities (Mumbai/Chennai):** High humidity amplifies HI despite moderate temperatures.
- **Arid regions (Jaipur):** Lower humidity moderates HI but intensifies dehydration risks.
- **Urban heat islands (Delhi):** Concrete landscapes elevate nighttime HI, linked to ~30% higher nocturnal mortality.

As a cornerstone of India's climate adaptation strategy, HI informs IMD alerts, workplace safety norms, and public health protocols. By translating complex interactions between temperature, humidity, and human physiology into actionable metrics, it bridges scientific rigor and lifesaving interventions in a warming world.

Drawing on trends from the past five years and the available literature, this study focuses on several major states in India including Andhra Pradesh, Bihar, Odisha, Punjab, Maharashtra, Telangana, Uttar Pradesh, West Bengal, and Gujarat, as critical regions for heat risk analysis. Due to data limitations, forecasts for temperature, humidity, and heat index (HI) are provided only for the capital cities of these states. Temperature forecasts are sourced from the AccuWeather portal for the period from March to mid-June 2025, detailing both maximum and minimum variations [102]. Monthly average relative humidity data are obtained from Weather & Climate; for Amaravathi, in the absence of local RH data, figures from the nearby city of Guntur were used [103]. The variations in higher (Table 5) and lower temperature (Table 6) and corresponding HI are tableted below.

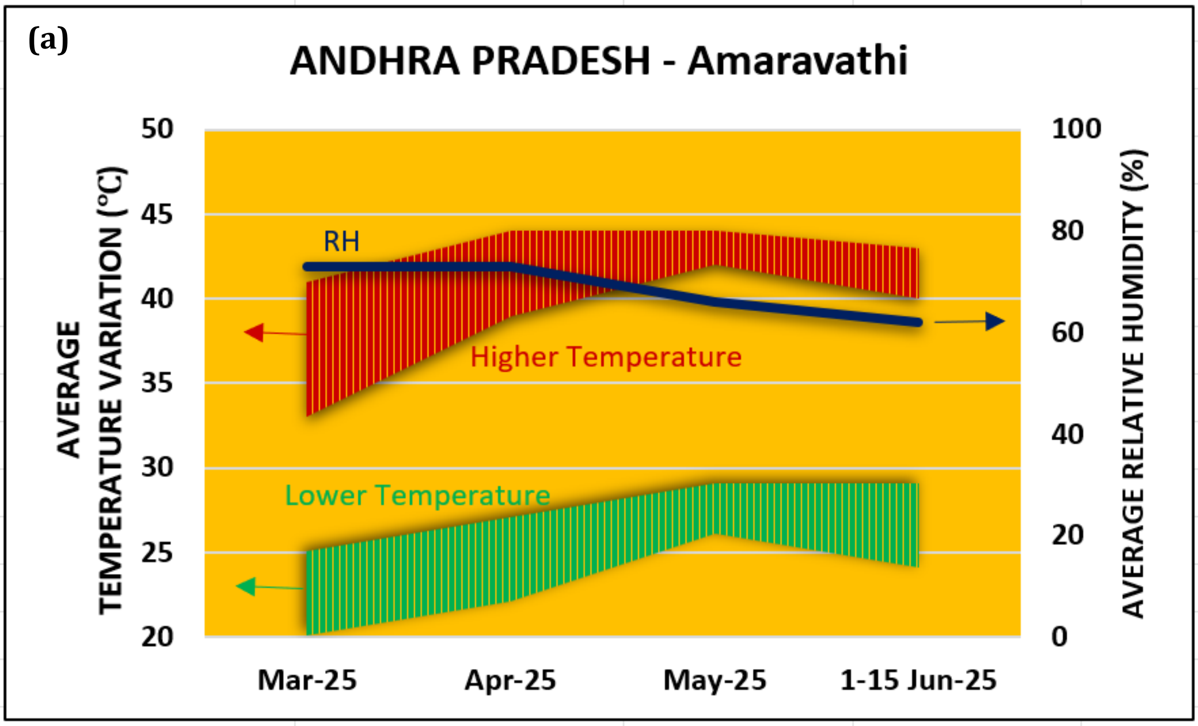
Table 5. HI corresponds to higher temperature variations.

Period	High Temperature (°C)		Avg. RH (%)	Heat Index (°C)	
	min	max		min	max
Mar-25	33	41	73	44.8	80.3
Apr-25	39	44	73	69.9	98.0
May-25	42	44	66	77.7	88.3
1–15 Jun-25	40	43	62	64.4	78.1

Table 6. HI corresponds to lower temperature variations.

Period	Low Temperature (°C)		Avg. RH (%)	Heat Index (°C)	
	min	max		min	max
Mar-25	20	25	73	20	25.5
Apr-25	22	27	73	22.2	29.1
May-25	26	29	66	27.2	32
1–15 Jun-25	24	29	62	24.1	31.4

Figure 4a presents the temperature extremes and average monthly RH for Amaravathi, while Figure 4b shows the corresponding heat index values. From March to mid-June 2025, Amaravathi sees two distinct temperature bands: higher temperatures range from 33°C to 44°C with heat index (HI) values occasionally surpassing 90°C, indicating "Extreme Danger," while lower temperatures hover between 20°C and 29°C, mostly within "Safe" to "Caution" zones. Although the drop in average relative humidity from about 73% to 62% slightly reduces overall heat stress, midday conditions linked to higher temperature variations remain critically high. Although heat indices based on lower temperature variations tend to indicate safer conditions, the higher daytime temperatures which are more relevant for outdoor activities, pose a significantly greater risk. Consequently, this analysis emphasizes the variations in higher temperatures and their associated heat index values for each city.



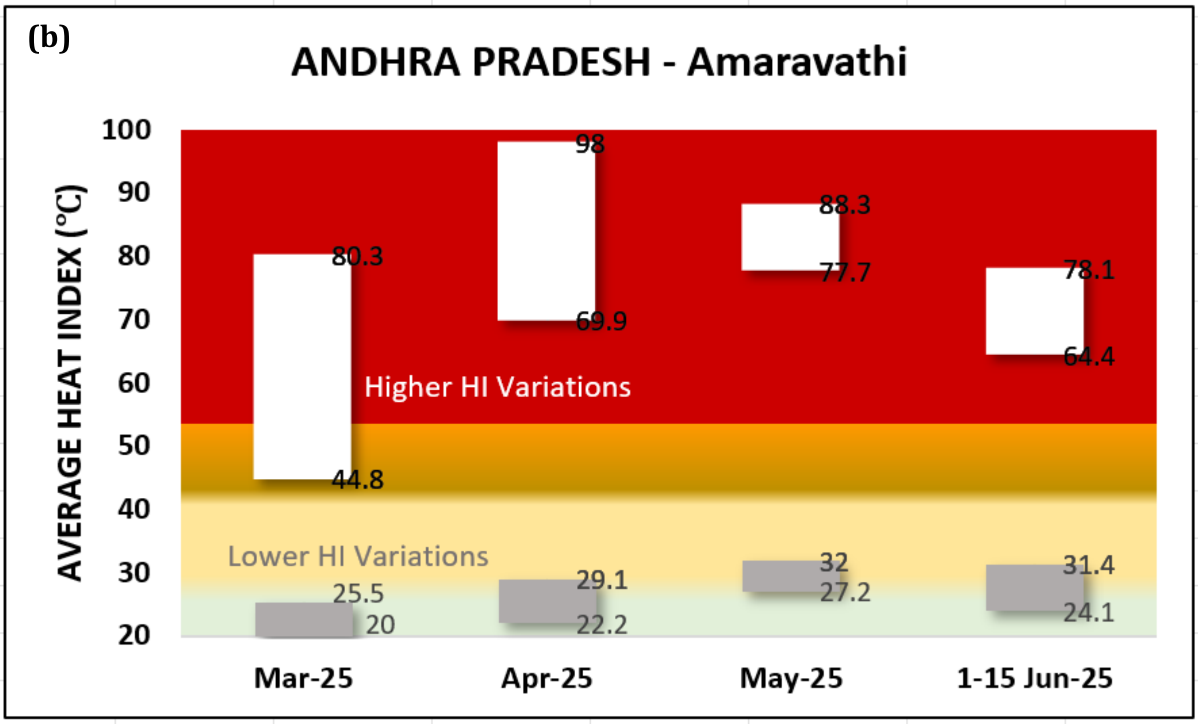
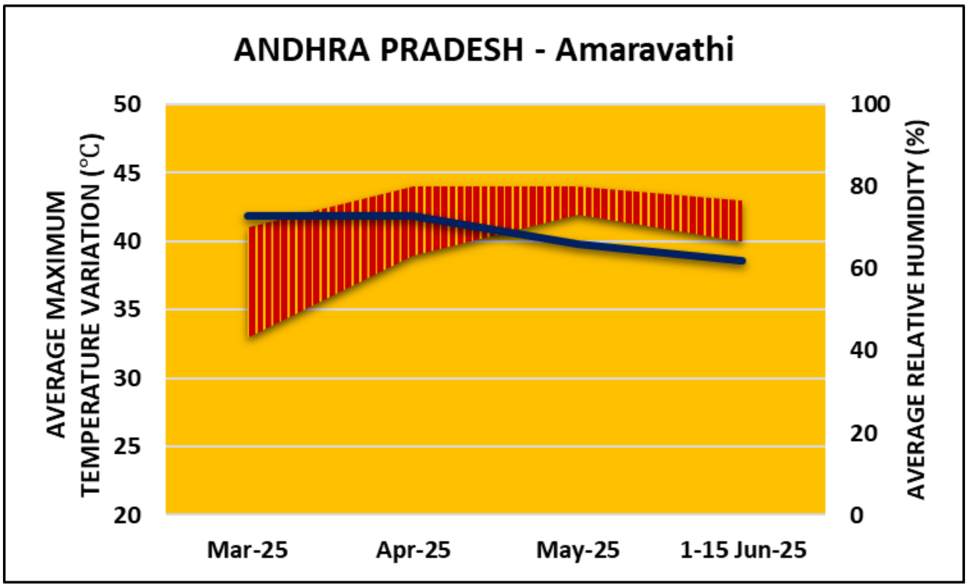
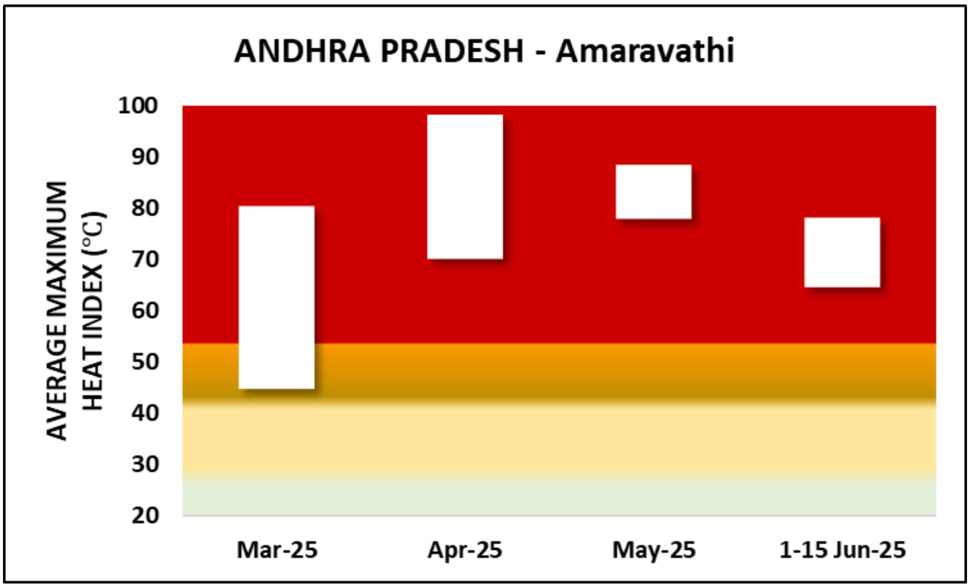


Figure 4. Temperature extremes and average monthly RH (a) and the corresponding heat index values (b) for Amaravathi from March to mid-June 2025.

ANDHRA PRADESH - Amaravathi

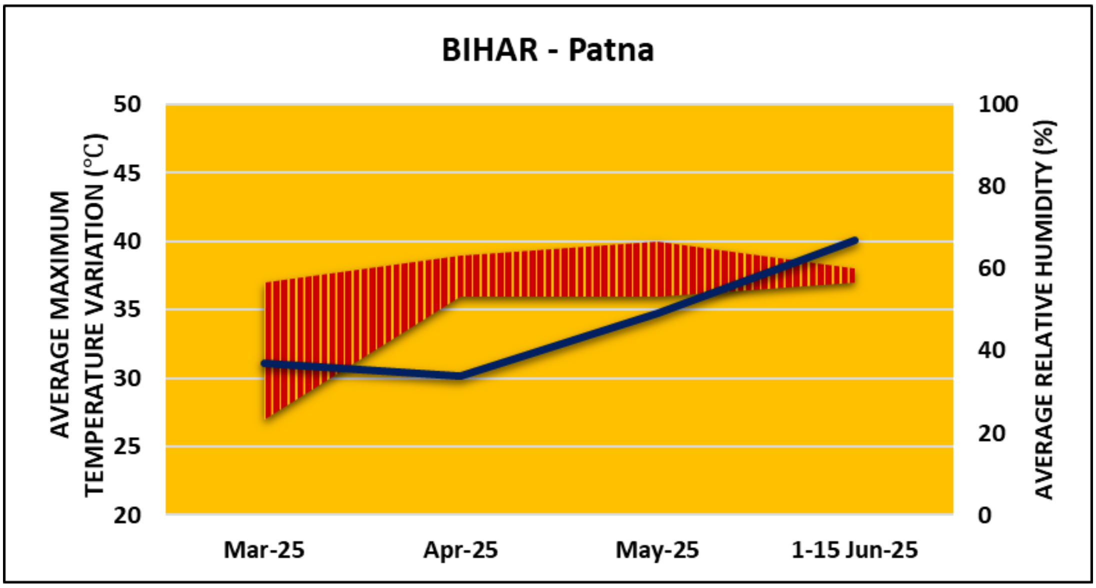


From March to early June 2025, Amaravathi experiences a concerning rise in heat stress, with higher temperature variations escalating from approximately 41°C in March to peaks of around 44°C in April and May, followed by a slight easing in early June. Although the average relative humidity decreases from 73% to 62% during this period, the corresponding heat index values remain critically high, reaching up to 98°C in April, which places outdoor activities at severe risk for heat-related illnesses.

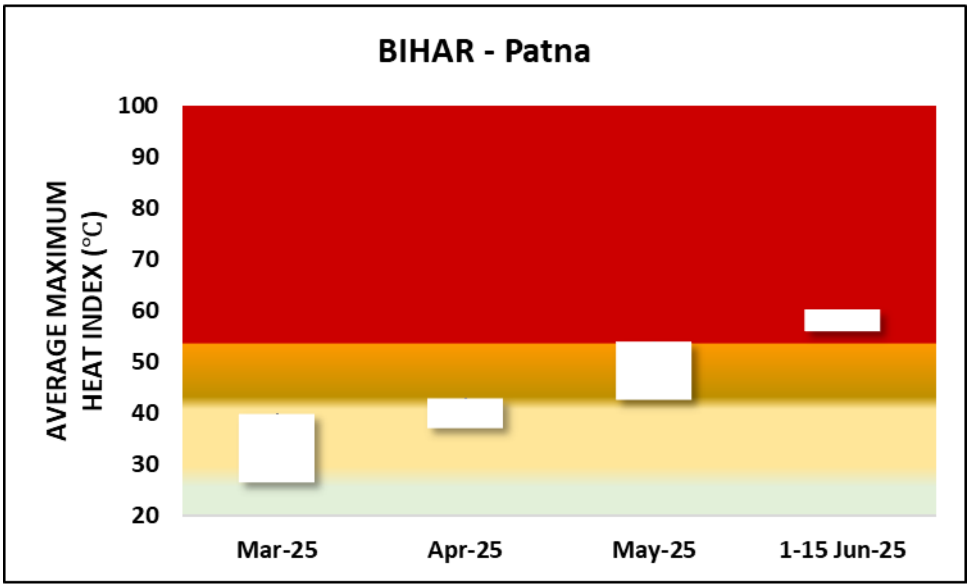


Mar-25	Lower values fall in the "Danger" range (sunstroke, muscle cramps likely) while peak values indicate "Extreme Danger" (heatstroke or sunstroke likely).
Apr-25	Consistently in the "Extreme Danger" range, with conditions highly likely to cause heatstroke or sunstroke.
May-25	Both minimum and maximum values are in the "Extreme Danger" range, posing severe risks for heat-related illnesses.
1-15 Jun-25	Although slightly lower than April, values still classify as "Extreme Danger," warranting significant caution for outdoor activities.

BIHAR - Patna

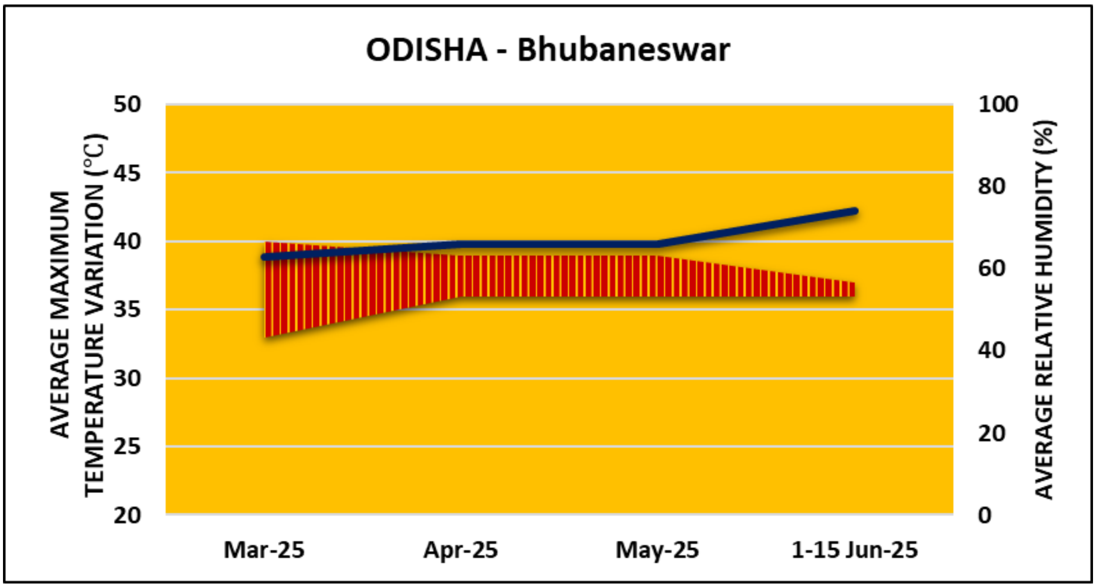


From March to mid-June 2025, Patna exhibits a clear upward trend in heat index values, indicating escalating heat stress risks. In March, values range from approximately 26.7°C to 40.1°C, suggesting conditions from low to moderate risk. By April, the heat index rises to between 37.3°C and 42.9°C, increasing the likelihood of heat-related discomfort and exhaustion. In May, the range escalates to 42.7°C – 54.1°C, signifying a shift toward severe health risks, and by early to mid-June, the index peaks at 56.1°C – 60.2°C, where conditions are deemed extremely dangerous for outdoor activities.

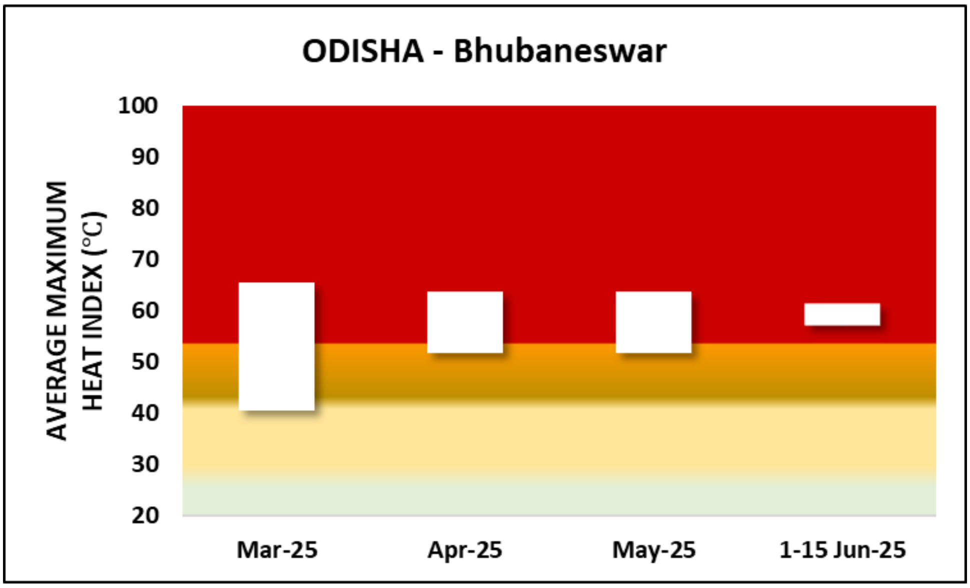


Mar-25	Ranges from low risk ("Caution") to moderate risk ("Extreme Caution"), indicating rising heat stress.
Apr-25	Indicates a shift toward "Danger," with increased likelihood of heat exhaustion and related symptoms.
May-25	Conditions span from "Danger" to "Extreme Danger," posing significant risks of heatstroke and sunstroke.
1-15 Jun-25	Falls entirely in the "Extreme Danger" range, where outdoor activities face a very high risk of severe heat-related illness.

ODISHA - Bhubaneswar

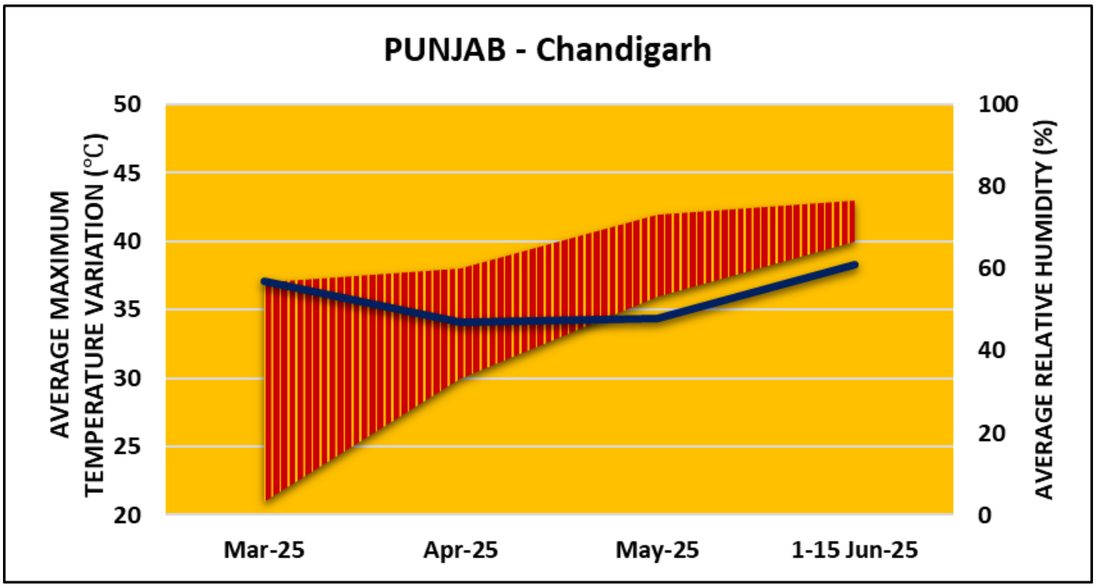


From March to mid-June 2025, Bhubaneswar experiences moderate heat stress, with heat index values fluctuating between 40.7°C and 65.3°C in March. April and May show a relatively stable trend, with values ranging from 51.7°C to 63.6°C, keeping conditions in the "Extreme Caution" to "Danger" zones. By early June, rising humidity pushes the heat index up to 56.9°C – 61.3°C, further increasing the risk of heat-related illnesses.

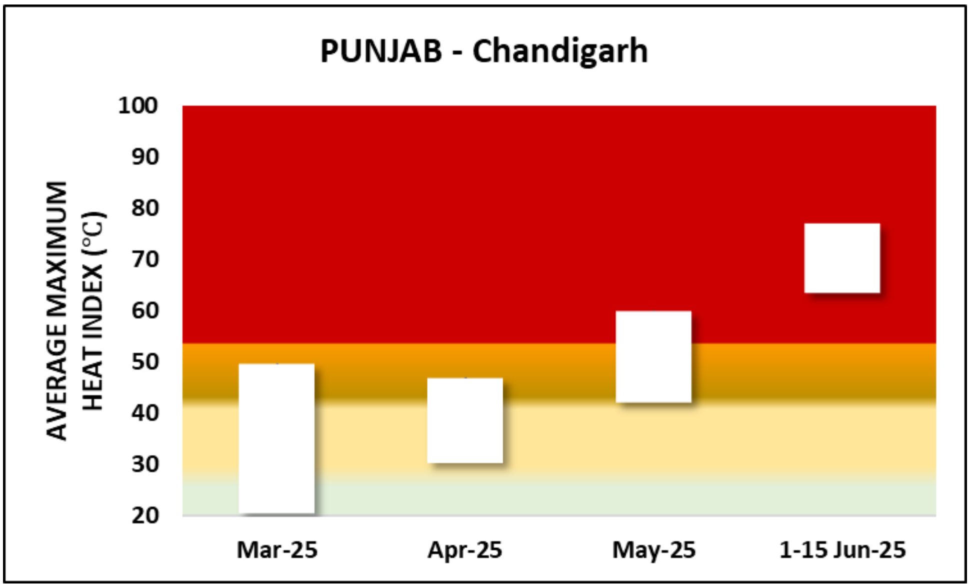


Mar-25	Falls within the "Extreme Caution" to "Danger" range, with risks of sunstroke and heat exhaustion increasing.
Apr-25	Conditions persist in the "Danger" range, with prolonged exposure posing significant health risks.
May-25	Similar to April, with continued risks of heat exhaustion and sunstroke for outdoor workers and vulnerable groups.
1-15 Jun-25	Heat index remains in the "Danger" range, with high humidity worsening the risk of heat stress and related illnesses.

PUNJAB - Chandigarh

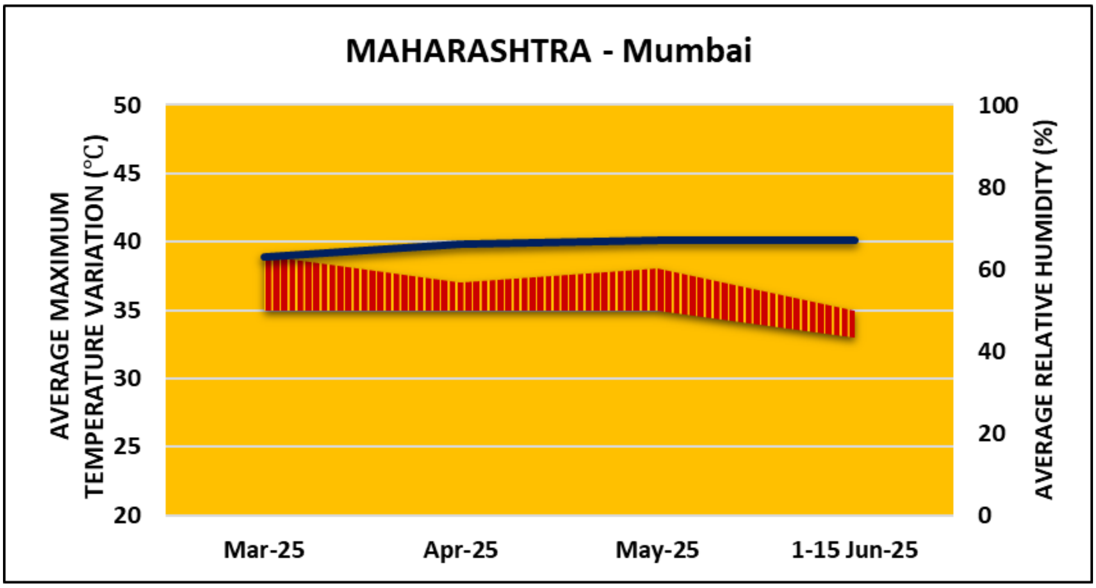


From March to mid-June 2025, Chandigarh experiences a steady rise in heat stress, with heat index values increasing from 20.7°C in March to 77°C by mid-June. March and April remain within moderate risk levels, but by May, conditions escalate into the “Danger” zone, with peaks reaching 60°C. The first half of June brings intensified risk, with a heat index of up to 77°C, posing serious health concerns for outdoor workers and vulnerable populations.

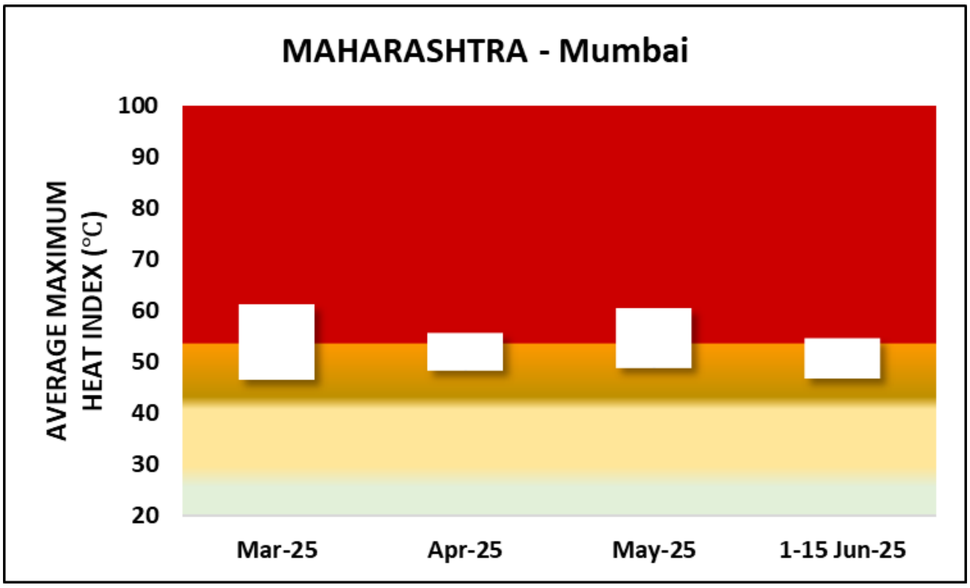


Mar-25	Mostly in the “Caution” range, with heat discomfort possible during peak hours.
Apr-25	Heat index rises but remains in “Caution” to “Extreme Caution” levels, requiring moderate precautionary measures.
May-25	Enters the “Danger” range, with heat exhaustion and sunstroke risks increasing significantly.
1-15 Jun-25	Peaks in the “Extreme Danger” zone, with high risks of heatstroke and severe heat-related illnesses.

MAHARASHTRA - Mumbai

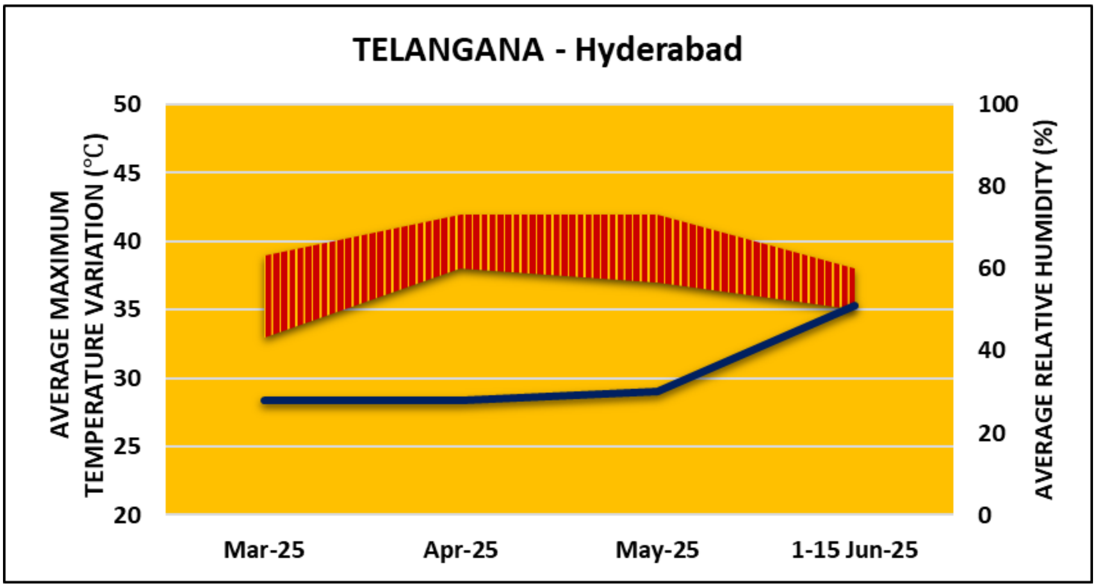


From March to mid-June 2025, Mumbai experiences consistently high heat index values due to elevated temperatures and humidity. The heat index fluctuates between 46.6°C and 61.1°C in March, rising slightly in April and May, with peak values reaching 60.2°C. Despite a slight temperature drop in early June, increased humidity keeps the heat index high, maintaining discomfort and health risks.

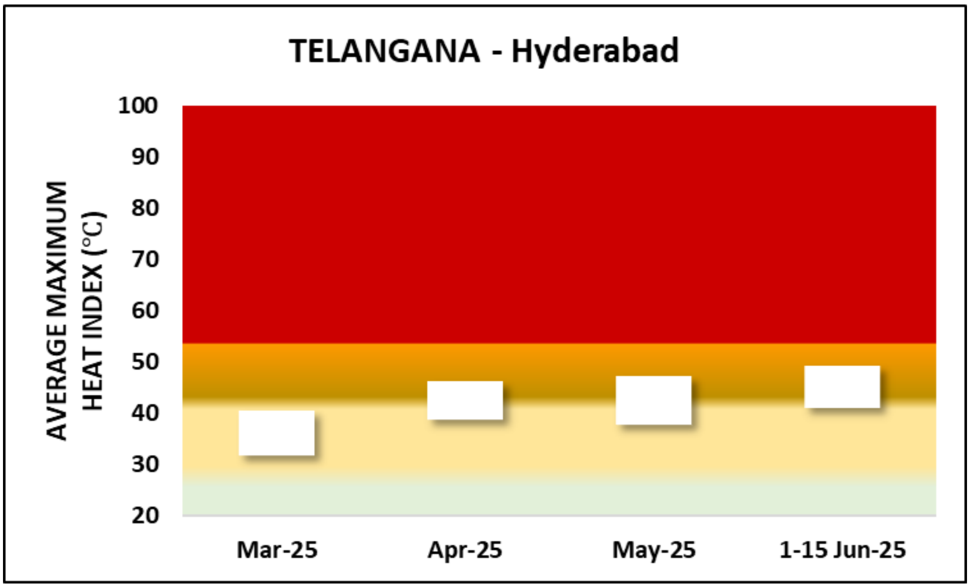


Mar-25	Falls in the "Extreme Caution" range, where prolonged exposure can cause heat exhaustion.
Apr-25	"Extreme Caution" persists, with heat exhaustion and cramps likely.
May-25	Enters the "Danger" range, where prolonged exposure can result in heat-related illnesses.
1-15 Jun-25	Continues in the "Extreme Caution" range, with high humidity exacerbating heat stress.

TELANGANA - Hyderabad

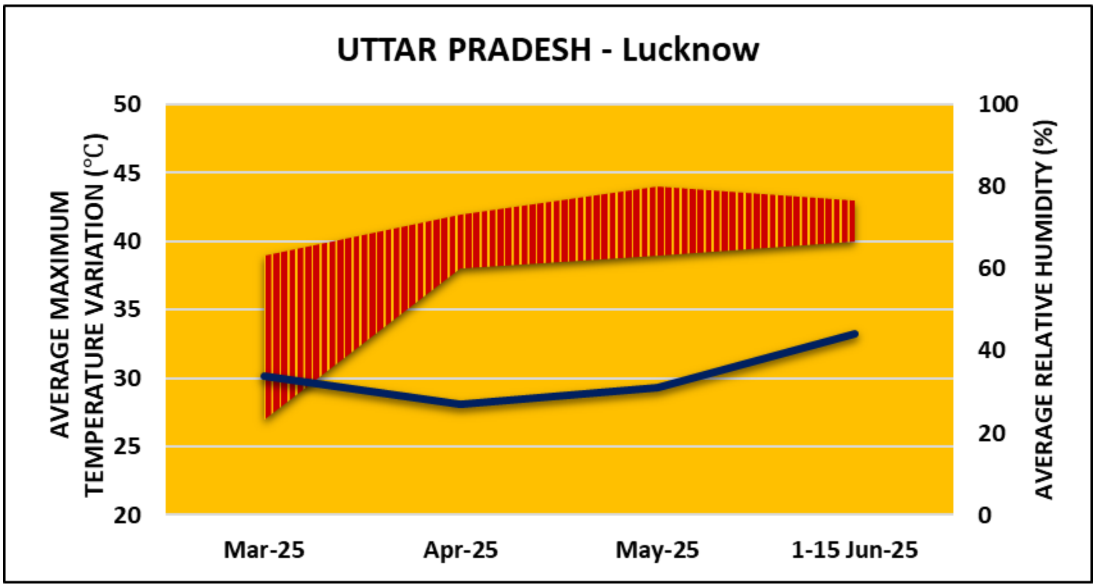


From March to mid-June 2025, Hyderabad faces progressively rising heat stress, with heat index values increasing from around 31.8°C in March to peaks of 47.3°C in May. While humidity remains relatively low early in the season, it rises significantly in June, intensifying the perceived heat. This persistent heat poses moderate to severe risks of heat-related illnesses, particularly in May and June.

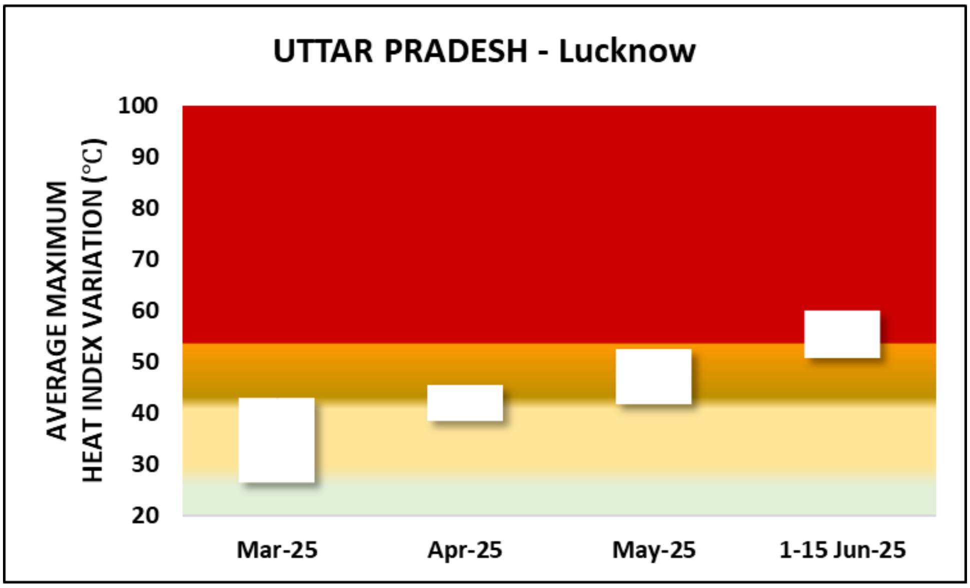


Mar-25	Falls in the “Caution” range, with potential fatigue and heat stress after prolonged exposure.
Apr-25	Approaches the “Extreme Caution” zone, increasing the likelihood of heat exhaustion.
May-25	Enters the “Danger” range, where prolonged exposure can cause heat-related illnesses.
1-15 Jun-25	Higher humidity exacerbates heat stress, maintaining risks in the “Danger” range.

UTTAR PRADESH - Lucknow

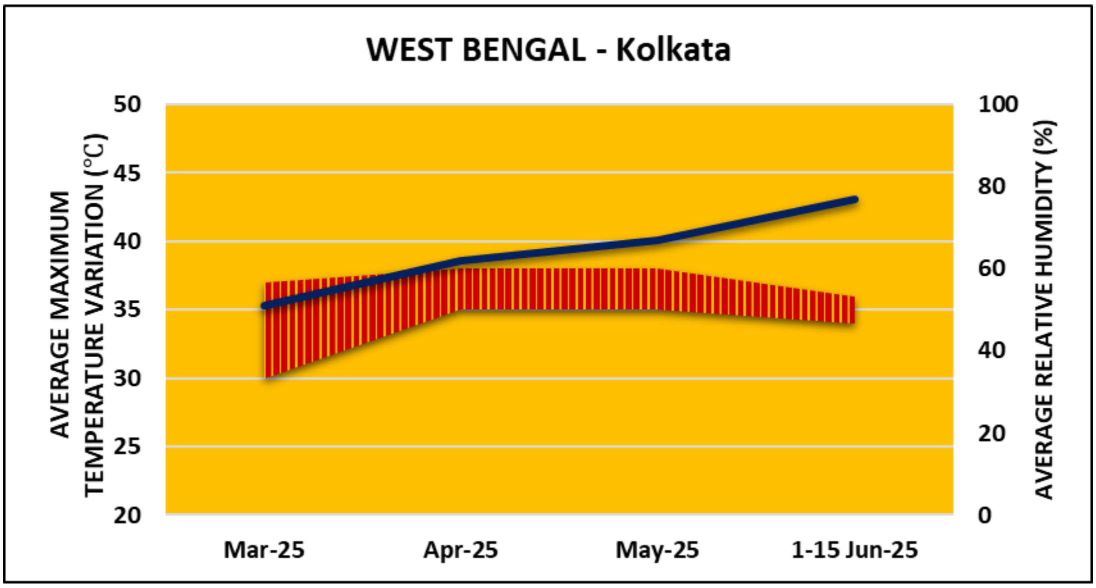


From March to mid-June 2025, Lucknow experiences a steady rise in heat stress, with heat index values increasing from 26.6°C in March to a peak of 60°C in mid-June. The combination of rising temperatures and increasing humidity in June exacerbates the perceived heat, elevating the risk of heat-related illnesses, especially in May and June.

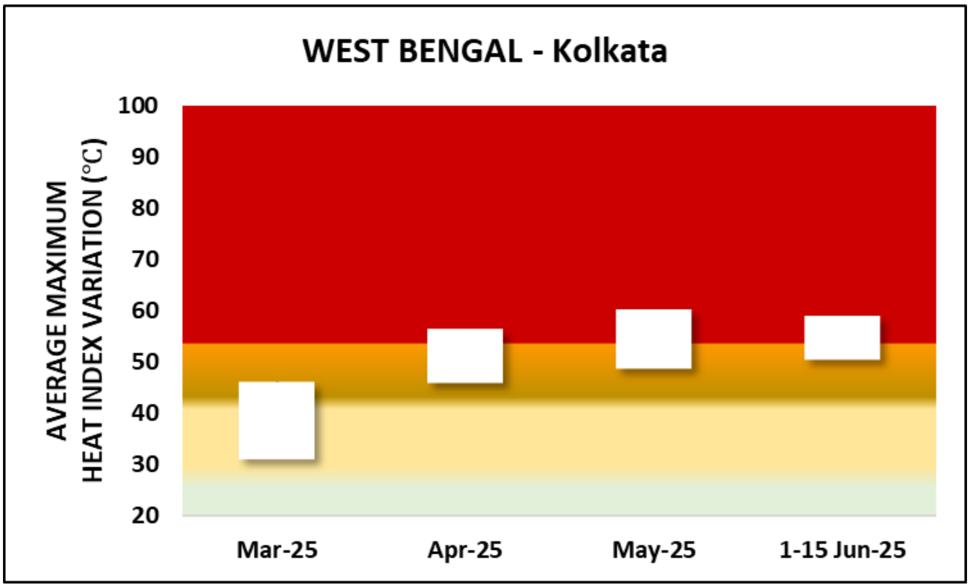


Mar-25	Falls within the "Caution" range, with fatigue and possible heat stress after prolonged exposure.
Apr-25	Moves into the "Extreme Caution" range, increasing risks of heat exhaustion and dehydration.
May-25	Reaches the "Danger" zone, where prolonged exposure may lead to heat cramps or heat exhaustion.
1-15 Jun-25	Enters the "Extreme Danger" range, with a high likelihood of heatstroke under extended exposure.

WEST BENGAL - Kolkata

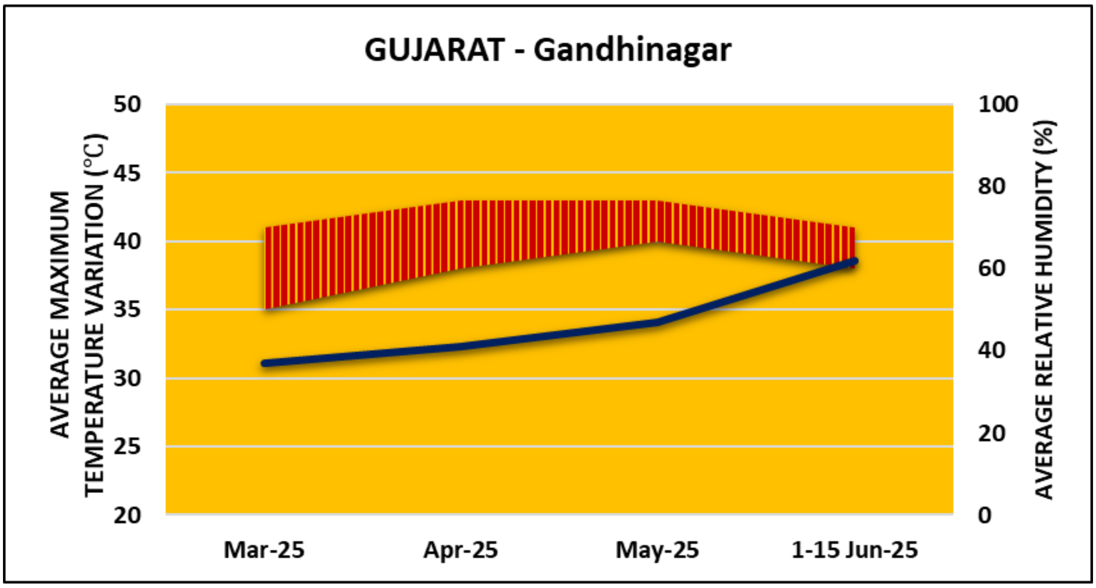


From March to mid-June 2025, Kolkata experiences an increasing heat index (HI), influenced by both rising temperatures and high humidity. By June, the HI reaches 59°C, pushing the city into dangerous heat stress levels. Kolkata's high humidity amplifies heat stress, making outdoor activities riskier, especially in May and June. Proper hydration and cooling measures are essential during this period.

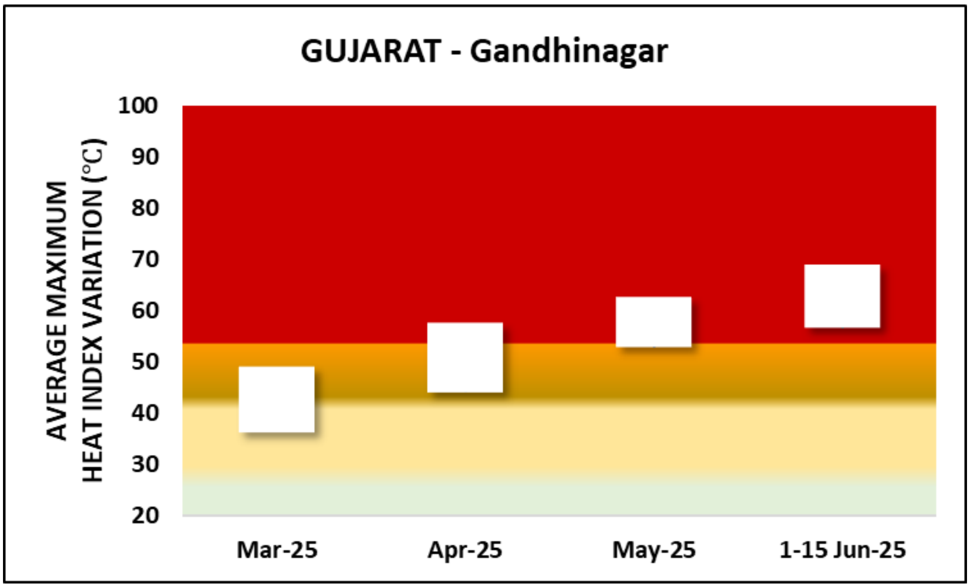


Mar-25	Mostly in the "Caution" range, with fatigue and potential heat stress after prolonged exposure.
Apr-25	Enters the "Extreme Caution" range, increasing the risk of heat exhaustion and dehydration.
May-25	Moves into the "Danger" zone, where prolonged exposure may cause heat cramps or exhaustion.
1-15 Jun-25	Approaching the "Extreme Danger" level, posing a high risk of heatstroke under prolonged exposure.

GUJARAT - Gandhinagar

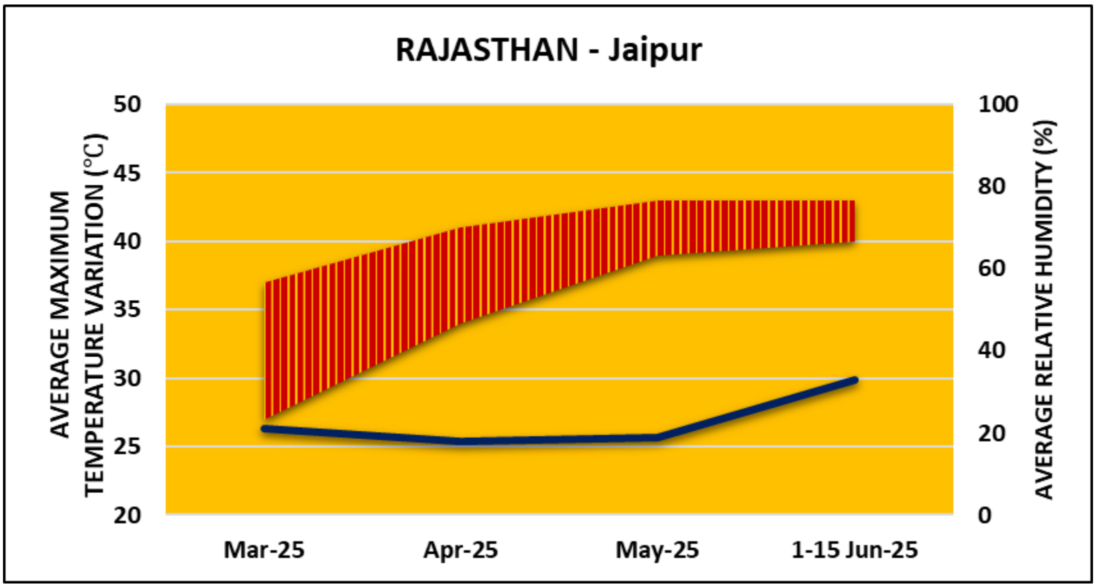


From March to mid-June 2025, Gandhinagar in Gujarat faces rising temperatures and humidity, leading to dangerously high heat index (HI) values. In March, the relative humidity is at 37%, leading to a moderate heat index of 49.1°C at its highest. By April and May, humidity levels rise to 41–47%, pushing the heat index beyond 57°C and 62.6°C, respectively. Gandhinagar's heat index of 68.8°C in June is one of the most extreme recorded, indicating severe heat stress. Protective measures like staying indoors, hydration, and avoiding physical exertion are essential.

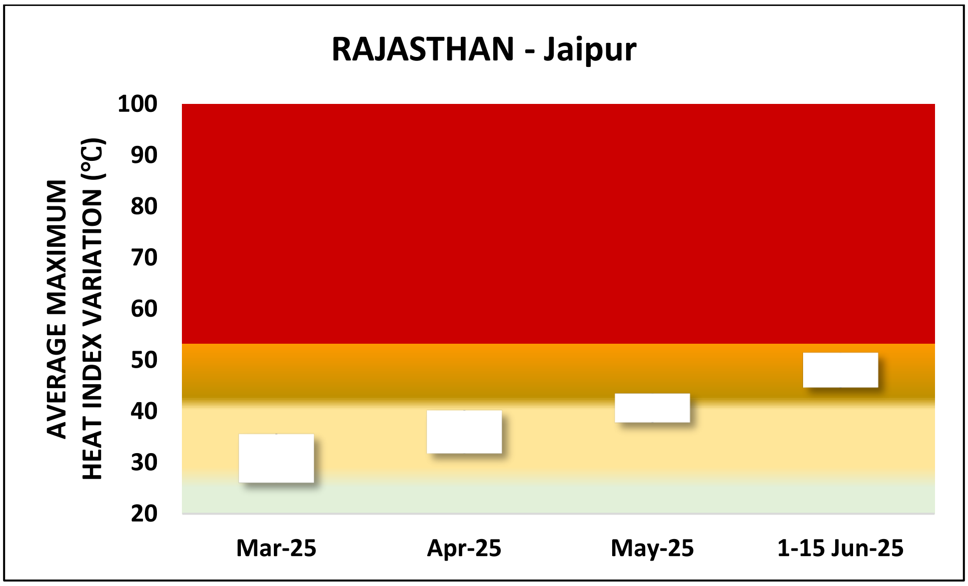


Mar-25	Moderate heat stress; caution advised for prolonged outdoor exposure.
Apr-25	Increased risk of heat exhaustion, requiring hydration and breaks from sun exposure.
May-25	Danger zone; risk of heat cramps and exhaustion. Long exposure can be hazardous.
1-15 Jun-25	Extreme danger; risk of heatstroke is very high, requiring strict cooling measures.

RAJASTHAN - Jaipur



From March to early June 2025, Jaipur experiences a steady rise in heat stress, with temperatures increasing from 37°C in March to peaks of around 43°C in April and May, persisting into early June. While the average relative humidity remains low, ranging from 18% to 33%, the heat index rises significantly, reaching 51.4°C in mid-June due to increasing moisture levels. The dry conditions in March and April provide some relief despite high temperatures, but by June, the combined effect of heat and humidity poses a growing risk for heat-related illnesses.



Mar-25	Warm but manageable; caution advised for outdoor activities.
Apr-25	Moderate heat stress; prolonged exposure can cause dehydration.
May-25	High risk of heat exhaustion; hydration is essential.
1-15 Jun-25	Danger zone; risk of heatstroke is significantly high.

Limitations of the Heat Index

For example, Amaravathi's forecasted March–June 2025 heat index (HI) values, flagged as "Extreme Danger" (≥54°C, 78-98°C) which highlight a critical flaw in relying solely on HI for heat-risk assessment. If correct, risks escalate beyond standard human/ecological survivability. While the region's soaring temperatures in April-25 (39–44°C) and high humidity (73%) undeniably pose severe risks (HI of 98°C), HI's methodology distorts reality: it assumes measurements in shade. Such values exceed both survivability thresholds and the Rothfusz equation's valid range, rendering HI unreliable for extreme conditions. This is where the Wet Bulb Globe Temperature (WBGT) becomes indispensable. While the Heat Index is a popular measure that estimates how hot it feels by combining temperature and relative humidity under shaded conditions, it has limitations at higher temperatures, particularly because it assumes light wind and absence of direct sunlight, factors that can significantly alter perceived heat stress. In contrast, the Wet Bulb Globe Temperature (WBGT) offers a more comprehensive assessment by incorporating not only temperature and humidity but also wind speed, solar radiation, and cloud cover, making it far more reliable for evaluating heat stress during strenuous outdoor activities, especially in direct sunlight. For a region where outdoor labour and agriculture dominate, transitioning to WBGT-guided policies, adjusting work hours, mandating rest cycles, is vital to prevent heat-related fatalities. While HI serves as a public alert, WBGT offers precision where it matters most: saving lives under the scorching Indian sun.

Table 7. Comparing WBGT and Heat Index [101].

	WBGT	HEAT INDEX (HI)
Measured in the sun	✓	×
Measured in the shade	×	✓
Uses temperature	✓	✓
Uses relative humidity	✓	✓
Uses wind	✓	×
Uses cloud cover	✓	×
Uses sun angle	✓	×

Table 8. Examples comparing WBGT and Heat Index [101].

Temp (°C)	Dew Point (°C)	RH (%)	Sky (%)	Wind (mph)	Heat Index (°C)	WBGT (°C)
32.2	18.3	42	05	03	33.3	31.6
32.2	18.3	42	65	13	33.3	27.2
37.8	21.1	39	65	05	42.2	32.8

Beyond HI and WBGT

India is experiencing an unprecedented escalation in heatwave-related health risks, particularly among vulnerable populations such as infants, older adults, and outdoor labourers. Traditional metrics like the Heat Index (HI) and Wet Bulb Globe Temperature (WBGT) remain essential for assessing immediate heat stress, yet they fall short in capturing the cumulative and complex effects of prolonged extreme heat. like the Universal Thermal Climate Index (UTCI), which integrates air temperature, humidity, wind speed, and mean radiant temperature to quantify perceived thermal stress, offer a more holistic understanding of human comfort in diverse environments. Complementing these, metrics/indices including Heatwave Number (HWN), Heatwave Frequency (HWF), Heatwave Duration (HWD), Heatwave Magnitude (HWM), and Heatwave Amplitude (HWA), derived from the Excess Heat Factor (EHF) and thresholds based on the 90th percentile of daily temperatures (TX90/TN90) capture and provide cumulative heat impacts and societal toll [61]. Thus, it may provide a more nuanced perspective on the persistence and severity of heatwaves, which is critical for understanding the broader societal impact.

In India, where long-term forecasts (3–6 months) remain unreliable due to climatic complexity, the India Meteorological Department (IMD) bridges gaps with actionable short-term solutions. Its 15-day heatwave forecasts and granular district- and subdivision-level alerts (district-wise, subdivision-wise) empower local authorities to act pre-emptively [104,105,106]. For instance, IMD's latest advisory flags regions like Odisha, Gujarat, Maharashtra, Telangana, West Bengal, Andhra Pradesh and Karnataka for temperatures exceeding 40°C during 14th to 20th March-25, escalating risks of heatstroke and coinciding with heightened transmission windows for vector-borne diseases like malaria and dengue [107]. However, this short-term forecast poses challenges for densely populated states and cities [107]. With limited time to mobilize resources, agencies in high-risk regions like Uttar Pradesh, Bihar, Maharashtra, West Bengal, Madhya Pradesh, Rajasthan, Gujrat and Andhra Pradesh may struggle to implement cooling centres, adjust work schedules, or issue health advisories before temperatures soar past 40°C, as highlighted in IMD's latest health advisory [107]. Enhancing predictive accuracy through AI-driven hyperlocal models that incorporate land-use, urban heat island effects, and demographic vulnerability is also imperative. Such a multi-index framework, combined with participatory governance and community-led adaptation measures, not only improves the precision of heat risk forecasts but also transforms reactive responses into proactive, life-saving interventions.

Assessment and monitoring strategies

A robust framework integrating biometeorological science, real-time health surveillance, and equity-driven vulnerability mapping is critical to address the escalating health risks posed by heatwaves. As global temperatures rise, the frequency and intensity of extreme heat events demand precision in monitoring and adaptive policy responses. Below, this study outlines the essential components of a scientifically grounded assessment strategy, drawing on global best practices and India-specific innovations.

1. Core Biometeorological Indicators

- **Wet-Bulb Temperature (TW)**

A critical threshold for human survivability, TW ≥32°C in humid regions (e.g., Kerala, Odisha) disrupts thermoregulation by impeding evaporative cooling, escalating risks of hyperthermia and organ failure [81,108,109,110]. Coastal cities like Mumbai face acute risks, where humidity amplifies heat stress even at moderate ambient temperatures [70,111]. Even in regions where maximum temperatures remained below 40°C, high humidity from the Bay of Bengal led to extremely dangerous heat stress conditions across southeastern India, with humidex (Hu heat index; combining the effect of heat and humidity) exceeding 54°C and WBGT surpassing 33°C, comparable to the severe heat experienced in northwest India [46,112].

- **Wet-Bulb Globe Temperature (WBGT)**

Integrates temperature, humidity, wind, and solar radiation to assess occupational heat exposure. WBGT ≥30°C necessitates work-rest cycles for outdoor labourers to prevent acute kidney injury, a condition affecting 40% of Indian construction workers during summer months [45,46, 81,108, 112,113,114,115].

- **Universal Thermal Climate Index (UTCI) and Heat Index**

The Universal Thermal Climate Index (UTCI) provides a more comprehensive evaluation of heat stress than the Heat Index, which is limited to temperature and humidity. By incorporating air temperature, humidity, wind speed, radiant heat, and physiological factors such as metabolic rate and clothing adaptation, UTCI offers a more accurate representation of human thermal strain. Research indicates that UTCI values exceeding 34–35°C are strongly associated with increased all-cause mortality (leading cardiovascular emergencies), particularly among vulnerable populations [46,70,112,116,117,118,119]. A 1°C rise beyond this threshold correlates with a 31.3% increase in mortality risk, highlighting the need for more precise heat stress assessments and targeted intervention strategies to mitigate the health impacts of extreme heat [71,120].

2. Health Metrics and Surveillance Systems

- **Excess Mortality Tracking**

Heatwaves are projected to intensify with climate change, posing a significant health risk [114]. If global emissions continue to rise at current rates (RCP 8.5; current growth rates of fuel use hold for much of the 21st century), India's mortality rate could increase by 10% by 2100, leading to an estimated 1.5 million additional deaths annually, comparable to the toll of all infectious diseases today. However, if countries strengthen climate commitments and curb emissions (RCP 4.5), this excess death rate could drop significantly, highlighting the critical need for global climate action [121]. An analysis of ten cities (2008–2019) found that extreme heatwaves, two consecutive days above the 97th temperature percentile led to a 14.7% increase in daily mortality [70]. Stronger associations were observed with higher intensity and longer-duration heatwaves. Annually, an estimated 1,116 deaths were attributed to heatwaves, underscoring the urgent need for adaptive measures. Even a slight rise in summer temperatures or an increase in heatwave days can drastically escalate heat-related mortality in India. Research indicates that a mere 0.5°C rise in summer mean temperature doubles the probability of mass heat-related deaths, while just two additional heatwave days increase this probability by 78% [122]. With future warming projected to reach 2.2°C to 5.5°C, the human toll could be devastating, emphasizing the urgent need for adaptive strategies. City- or region-specific mortality study could be more reliable [70,123,124]. Standardized ICD-10 coding (e.g., T67.0 and T67.01 for heatstroke) reduces underreporting, yet gaps persist in rural regions due to fragmented death registries [125,126,127,128].

- **Morbidity Indicators**

Morbidity indicators are critical for assessing the health burden of heatwaves, with hospitalizations for heatstroke, dehydration, and acute kidney injury serving as key markers [108,127,129]. Heatstroke, a severe failure of thermoregulation, results in multiorgan dysfunction and is classified into two forms: classic heatstroke, caused by prolonged environmental heat exposure, and exertional heatstroke, driven by excessive metabolic heat production during physical exertion [130,131]. Both forms pose life-threatening complications, including cardiovascular collapse, rhabdomyolysis, acute kidney injury, hepatic dysfunction, and disseminated intravascular coagulation (DIC). The progression from heat stress to heatstroke involves systemic inflammatory responses, circulatory failure, and irreversible organ damage, highlighting the urgency of early recognition and intervention [131].

Emerging morbidity indicators for heatstroke encompass central nervous system (CNS) dysfunction (e.g., confusion, seizures, coma), multiorgan failure (renal and hepatic injury, rhabdomyolysis), and coagulation abnormalities such as DIC [131,132]. These pathophysiological manifestations stem from thermoregulatory failure and systemic inflammatory cascades, necessitating precise clinical monitoring and timely therapeutic interventions. While immediate management through rapid cooling, fluid resuscitation, and intensive care support remains crucial, preventive strategies are paramount. Strengthening heat adaptation measures, such as modifying outdoor work schedules, enhancing public awareness campaigns, and addressing socioeconomic disparities, can significantly mitigate heat-related morbidity [131]. Additionally, advancing research on genetic susceptibility, novel biomarkers, and targeted treatment strategies will refine risk assessment and improve clinical outcomes in the face of escalating climate-related heat hazards.

- **Real-Time Health Dashboards**

Real-time health dashboards are pivotal in heatwave preparedness, integrating meteorological data with healthcare surveillance to facilitate rapid response strategies. The Ahmedabad Heat Action Plan (HAP) exemplifies this approach by incorporating Indian Meteorological Department (IMD) data with hospital records to trigger tiered heat alerts (orange/red) and deploy mobile health units during extreme heat events [44]. These systems are essential for protecting vulnerable populations and optimizing resource allocation in public health responses.

Beyond Ahmedabad, Heat Health Early Warning Systems (HHEWS) are advancing globally, leveraging real-time temperature, humidity, and morbidity data to predict heat-related health risks [133]. Initiatives such as the Global Heat Health Information Network (GHHIN) and National Weather Service's (NWS) HeatRisk system provide science-based decision tools that enhance emergency preparedness [127]. Similarly, the EXTREMA project, funded by the European Commission, integrates satellite thermal imaging with epidemiological data, offering personalized heat-risk assessments via mobile applications while enabling municipal authorities to manage cooling centres and deploy emergency interventions effectively [127,134].

India's expanding network of city- and region-specific Heat Action Plans (HAPs) underscores the necessity of scaling real-time health monitoring systems nationwide. Centralization of fragmented or regional steps could be more reliable; for example, the 'early warning mechanism' through town specific heat action plan and corporation of OSDMA in Odisha [81]. These dashboards track critical morbidity indicators, including heatstroke, dehydration, acute kidney injury, and emergency hospital visits, allowing for timely public health interventions. Public access to reporting nearby deaths through a centralized portal, initially categorized as suspected and later validated with medical proof, could enhance transparency, bridge reporting gaps, and refine assessment methodologies. However, implementing safeguards against duplicate entries and ensuring cross-verification with official health records would further strengthen the reliability of this approach. Strengthening inter-agency coordination, data-driven decision-making, and public awareness initiatives will be key to enhancing India's resilience to intensifying heatwaves, ensuring that early warnings translate into effective life-saving measures.

3. Vulnerability Mapping and Equity Considerations

Vulnerability mapping is a vital tool in understanding and addressing the disparate impacts of heatwaves across India, where both individual and regional factors, including physiological susceptibility, socioeconomic status, and infrastructural disparities, contribute to heightened health risks [135,136,137]. Recent studies employing Geographic Information System (GIS) tools and high-resolution demographic data have enabled the development of comprehensive Heat Vulnerability Indices (HVIs). These indices aggregate environmental factors (e.g., urban heat island intensity, land cover), sociodemographic attributes (e.g., age distribution, income levels), and health metrics (e.g., chronic disease prevalence) to identify local hotspots of risk. For instance, a study introduced a Heat Health Risk Index (HHRI) for 37 major Indian cities, utilizing geospatial and socio-ecological data to pinpoint areas with potential heat health risks [138]. Cities with populations exceeding 10 million, such as Mumbai, Chennai, Kolkata, and Ahmedabad, face the highest heat health risks. Conversely, cities like Ludhiana, Theni, Amritsar, and Nabarangpur exhibit higher liveability indices, indicating greater adaptive capacity and lower exposure to heat risks. The study also found that cities with low green cover are highly vulnerable, resulting in elevated HHRI scores and reduced adaptive capacity. Furthermore, cities lacking vegetation and characterized by barren lands typically experience higher land surface temperatures. These findings underscore the importance of incorporating socioeconomic factors, such as per capita income, poverty levels, health services, education, and mortality rates, into future research to better understand the relationship between local climate zones and heat health risk.

These refined assessments are crucial for tailoring adaptive strategies at the community or block level, ensuring that interventions, such as enhanced cooling infrastructure and targeted public health campaigns, effectively reach the most vulnerable populations, particularly in urban slums and resource-poor rural areas. The integration of GIS tools and satellite-derived data has further advanced the development of high-resolution vulnerability indices. Studies utilized such technologies to map urban socio-economic vulnerability related to heat risk, considering factors like heat exposure, sensitivity, and adaptive capacity while incorporating justice and equity [127,135,137,139,140]. These methodologies enable the identification of specific areas and populations at heightened risk, informing targeted interventions to mitigate the adverse effects of urban heat islands.

4. Advanced Monitoring Infrastructure

Advanced monitoring infrastructure is critical for effective heatwave management and public health response in India. Recent developments integrate AI-driven early warning systems with high-resolution satellite remote sensing and real-time meteorological data, combined with district-level socioeconomic indicators, to construct comprehensive Heat Vulnerability Indices (HVI) [36,127,135,137,139,141,142]. For example, a PCA-based HVI utilizing census data, health reports, and satellite-derived land surface temperatures has identified central Indian districts as high-risk areas, with moderate correlations observed between HVI and summer land surface temperature (from satellite data), suggesting a relationship between higher temperatures and heat vulnerability [81,143]. Moreover, it shows an inverse relationship (moderate negative correlation) with urbanization signifying a possible greater vulnerability threat in rural areas. Since the majority of Indians reside in rural areas, this could have important implications specifically in agriculture and outdoor activities. In parallel, Thane City's Heat Action Plan (HAP) integrates IMDAA (Indian monsoon data assimilation and analysis) reanalysis data, Regional Climate Models, and Landsat-8 imagery, augmented by indices like NDVI (normalised difference vegetation index), MNDWI (modified normalised difference water index), and NDBI (normalised difference built-up index), to spatially map urban heat islands and guide targeted interventions, such as cooling centres and community outreach programs [141]. AI-enhanced early warning systems (EWS) for heatwaves employ machine learning to synthesize multi-scale datasets, including global climate projections from the Coupled Model Intercomparison Project (CMIP) under representative concentration pathways (RCPs) and localized socio-economic scenarios from shared socio-economic pathways (SSPs) [36,111,144,145]. These systems integrate outputs from regional climate models (RCMs), which dynamically downscale CMIP's coarse-resolution projections to capture subnational climate variability, such as urban heat islands or coastal humidity gradients [146,147]. By harmonizing RCM-refined temperature extremes with SSP-driven socioeconomic variables, such as population density, healthcare access, and urbanization trends, AI algorithms improve hazard-to-impact forecasting accuracy. This enables precise predictions of heatwave frequency, duration, and health risks (e.g., mortality in vulnerable demographics), while contextualizing adaptive capacity across regions. Consequently, these systems inform targeted mitigation strategies, such as deploying cooling centres in high-risk urban wards or adjusting agricultural schedules in heat-prone rural districts, thereby bridging global climate projections with actionable local resilience planning. Concurrently, advancements in wearable biosensors and remote tracking technologies enable real-time monitoring of physiological responses, enhancing individual-level risk assessment despite challenges like power consumption and signal drift [148,149,150]. Future directions include the development of hyperlocal climate models, interdisciplinary collaborations, and ethical AI governance to minimize biases, thereby bridging technological precision with community-led adaptation measures. This integrated, data-driven approach not only refines climate-health projections but also supports timely deployment of emergency services and informed policymaking, ultimately strengthening urban resilience and protecting vulnerable populations.

5. Research Priorities and Innovation

- **Chronic Heat Exposure and Pollution-Heat Synergies**

Chronic exposure to elevated temperatures, particularly in the context of compound drought-heatwave (CDHW) events, presents significant health risks and socioeconomic challenges. Long-term exposure to extreme heat is associated with cardiovascular strain, cognitive decline, and increased mortality risks, disproportionately affecting vulnerable populations such as outdoor workers and elderly individuals [151]. In South Asia, projections indicate that under high-emission scenarios (RCP8.5), heatwave days could increase from 45 to 78 per year by 2050 [111]. The synergistic interaction between heatwaves and air pollution, particularly fine particulate matter ($PM_{2.5}$) and ground-level ozone, further exacerbates respiratory and cardiovascular diseases [45,57,70,108,111,114,124,127,133,152,153,154,155]. Empirical studies highlight that during extreme heat events, $PM_{2.5}$ concentrations surge, intensifying systemic inflammation and oxidative stress [156]. The recent heatwave in the Indian subcontinent has critically impacted various interconnected systems, notably leading to increased dust and ozone levels, which have significantly exacerbated air pollution [37]. This deterioration in air quality, coupled with extreme heat, has been linked to a 14.7% rise in daily mortality during periods where temperatures exceeded the 97th percentile for two consecutive days [70]. Furthermore, a $10 \mu g/m^3$ increase in $PM_{2.5}$ concentration correlates with a 1.4% uptick in daily mortality, underscoring the compounded health risks posed by elevated temperatures and particulate matter [157]. Alarmingly, in major Indian cities, approximately 7.2% of all annual deaths are attributable to $PM_{2.5}$ levels surpassing the World Health Organization's safe exposure guidelines, with Delhi experiencing around 12,000 such fatalities annually [157,158]. Moreover, air pollution has led to respiratory diseases in about 70% of people in an Indian city; particularly it is more severe in central and eastern India [151,159]. Also, urbanization contributes to the stagnation of atmospheric pollutants during heatwaves, prolonging exposure and increasing the risk of heat-related illnesses. These findings highlight the urgent need for integrated strategies to mitigate the dual threats of extreme heat and air pollution.

- **Adaptive Infrastructure and climate change integration**

Adaptive infrastructure strategies that integrate green, blue, and engineered solutions have been proven quite effective in mitigating such heat/climate and health related risks. Urban greening, including tree canopies, green walls, and rooftop gardens, can lower urban temperatures through evapotranspiration and shading [154]. A study in Sydney found that an increase of two million well-irrigated trees could decrease the Universal Thermal Climate Index (UTCI) by 0.2°C to 1.7°C during heatwaves, subsequently reducing heat-related mortality [160]. Similarly, blue infrastructure, such as ponds, lakes, and rivers, provides evaporative cooling, reducing surrounding air temperatures by 5–20% depending on size and placement [154]. However, challenges such as increased humidity, mosquito breeding, and water management complexities must be addressed for optimal implementation. Reflective and permeable materials offer another layer of heat mitigation. Cool and green roofs and reflective pavements significantly reduce heat absorption, with studies (in context of Australia) demonstrating a reduction of peak ambient air temperatures by up to 2.7°C when combined with urban greening [154,161]. Nonetheless, it consequently decreases the peak electricity demand and the total annual cooling load by 2% and 7.2%, respectively [161]. However, their efficacy varies across climatic zones, necessitating region-specific adaptations. In addition, equitable access to cooling infrastructure remains a pressing concern, as low-income communities often lack access to air conditioning or passive cooling solutions.

Integrating climate-resilient urban planning with social equity considerations is essential to ensure that adaptation strategies are effective and inclusive. Emerging frameworks advocate for real-time monitoring systems that bridge climate projections with localized vulnerability mapping. By leveraging artificial intelligence (AI) to synthesize climate models, pollution trends, and demographic data, policymakers can develop targeted interventions, such as cooling centres in high-risk areas and urban heat mitigation strategies tailored to local conditions. Ultimately, a holistic, interdisciplinary approach, merging climate science, public health, and urban planning, is critical to transforming fragmented adaptation efforts into cohesive, long-term resilience strategies. Addressing climate change presents an opportunity to drive transformative improvements in public health, but success depends on sustained, health-centred action. This requires formal training on climate and health within medical education, empowering Indigenous and frontline communities in policy-making, and integrating health into all climate strategies through cross-sector collaboration [45]. However, these efforts alone are not enough, they must be backed by achieving the Paris Agreement's mitigation goals, as failing to curb emissions will undermine any health protection measures.

Questions for Further Research

1. **How can India's fragmented health data systems be unified to enable real-time, district-level heat mortality tracking?**

Exploring blockchain-based mortality registries and interoperability standards for rural clinics. How can blockchain-based mortality registries unify India's fragmented health data systems for real-time, district-level heat mortality tracking [162,163]*?*

2. **What are the efficacy thresholds for urban heat mitigation strategies (e.g., cool roofs vs. green walls) in varying climatic zones?**

Conducting RCTs (randomized controlled trials) in cities like Jaipur (arid) and Chennai (tropical) to assess context-specific benefits. What efficacy thresholds exist for urban heat mitigation strategies (e.g., cool roofs vs. green walls) across climatic zones [154,164,165]*?*

3. **How can hyperlocal air temperature mapping, integrating machine learning and remote sensing, enhance early heatwave detection and adaptation strategies in both urban and rural areas?**

This research aims to assess the feasibility of hyperlocal temperature mapping to improve heat resilience across diverse landscapes, considering distinct environmental and infrastructural parameters in urban and rural settings [166,167,168,169,170].

4. **Can genomic markers predict individual susceptibility to heatstroke, enabling personalized early warnings?**

Investigating polymorphisms in thermoregulatory genes (e.g., Transient Receptor Potential Vanilloid, TRPV1) across Indian populations. Can genomic markers (e.g., TRPV1 polymorphisms) predict individual susceptibility to heatstroke, enabling personalized warnings [171,172,173,174,175]*?*

Interested in next phase of study?

Join Our Next Research Initiative: Exploring the Multifaceted Impacts of Heatwaves.

We are embarking on a comprehensive study to delve deeper into the diverse effects of heatwaves. We invite communities, NGOs, industries, individuals, and researchers worldwide to collaborate with us in this endeavour. Your participation can significantly contribute to understanding and mitigating the challenges posed by extreme heat events.

Upcoming Research Areas:

- **Impact on Animal Life:** Investigating how heatwaves affect wildlife and domestic animals, including health, behaviour, and habitat changes.
- **Water Security and Hydrological Stress:** Assessing the influence of prolonged heat on water resources, availability, and quality.
- **Agriculture and Food Security:** Analyzing the repercussions of heatwaves on crop yields, soil health, and food supply chains.
- **Energy Demand and Grid Stability:** Exploring the increased energy consumption during heat events and its impact on power systems.
- **Urban Infrastructure and the Heat Island Effect:** Examining how heatwaves intensify urban heat islands and affect city infrastructure.
- **Economic and Social Equity:** Understanding the socioeconomic disparities exacerbated by heat-related challenges.

Your involvement is crucial. If you are interested in participating or contributing to these studies related to the adverse effects of heatwaves, please reach out to us at info@rinolyst.com. Together, we can build resilience and develop strategies to combat the adverse effects of heatwaves on our environment and society.

NEXT PHASE OF STUDY

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