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Research article

Heatwave health risk index for Karnataka, India

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A R T I C L E I N F O

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A B S T R A C T

Introduction: With the rise in global temperatures due to climate change, heatwaves are predicted to become more frequent, prolonged, and intense. Safeguarding people's health, well-being, and quality of life from the effects of climate change and its extremes is now a priority for policymakers and international and national governments. High-risk areas, zones, districts, and communities must be recognized ahead of time to better guide planning and preparedness. This study focused on assessing the heatwave occurrence and developing a heatwave health risk index (HHRI) at the district level in Karnataka.
Materials & Method: A comprehensive framework by the Intergovernmental Panel on Climate Change on a climate change risk assessment methodology incorporating hazard, exposure, and vulnerability was employed to develop the HHRI under the current climate change scenario. Among the crucial determinants influencing the HHRI, 11 indicators were selected, encompassing heatwave occurrence, diurnal temperature ranges, population density, outdoor labor population, population commuting on foot, number of medical institutions, green cover, elderly population, people with disabilities, multidimensional poverty index, and health index.
Results: The districts with higher hazard, exposure, and vulnerability were identified and mapped along with their risk driving key factors. Among the 31 districts examined in our study, Bidar, Kalaburagi, Gadag, and Dharwad districts were classified in the very high-risk category, whereas 9 were classified in the high-risk category.
Conclusion: The study findings on the variations in heatwave health risks among districts will enable policymakers to prioritize and execute targeted strategies to successfully reduce climate impacts.

1. Introduction

Climate change is a pressing issue due to its' far-reaching consequences, which threaten human well-being, infrastructure, and the environment. The urgency to address climate change is heightened by the necessity to mitigate its impacts and foster resilience against extreme weather events [1,2]. Notably, the frequency and intensity of extremes of heat (including heatwaves) have increased, on the global scale since 1950 [3]. Heatwaves are characterized by prolonged periods of intense heat that can significantly affect human health, agricultural productivity, workforce, etc., and can lead to economic losses [4].

There is no universally accepted definition of heatwaves; various countries have distinct definitions of heatwaves based on their specific local conditions. The Indian Meteorology Department (IMD) declares a 'heatwave' when a weather station's maximum temperature reaches at least 40°C (plains) or 30°C (hilly areas) for two consecutive days in a meteorological sub-division. Heatwaves in India, usually occurring between March and June, have exhibited an increased frequency and duration, with projections indicating a future trend towards greater prevalence and duration [5–7]. Moreover, in India's heatwave-prone areas, the total duration of heatwaves has increased by around 2.5 days during the last 30 years [7].

Heatwaves are among the most hazardous natural events, yet they often do not receive adequate attention compared with more visibly violent hazards such as tropical cyclones or floods [8]. The true toll of a heatwave, including mortality and health impacts, is not

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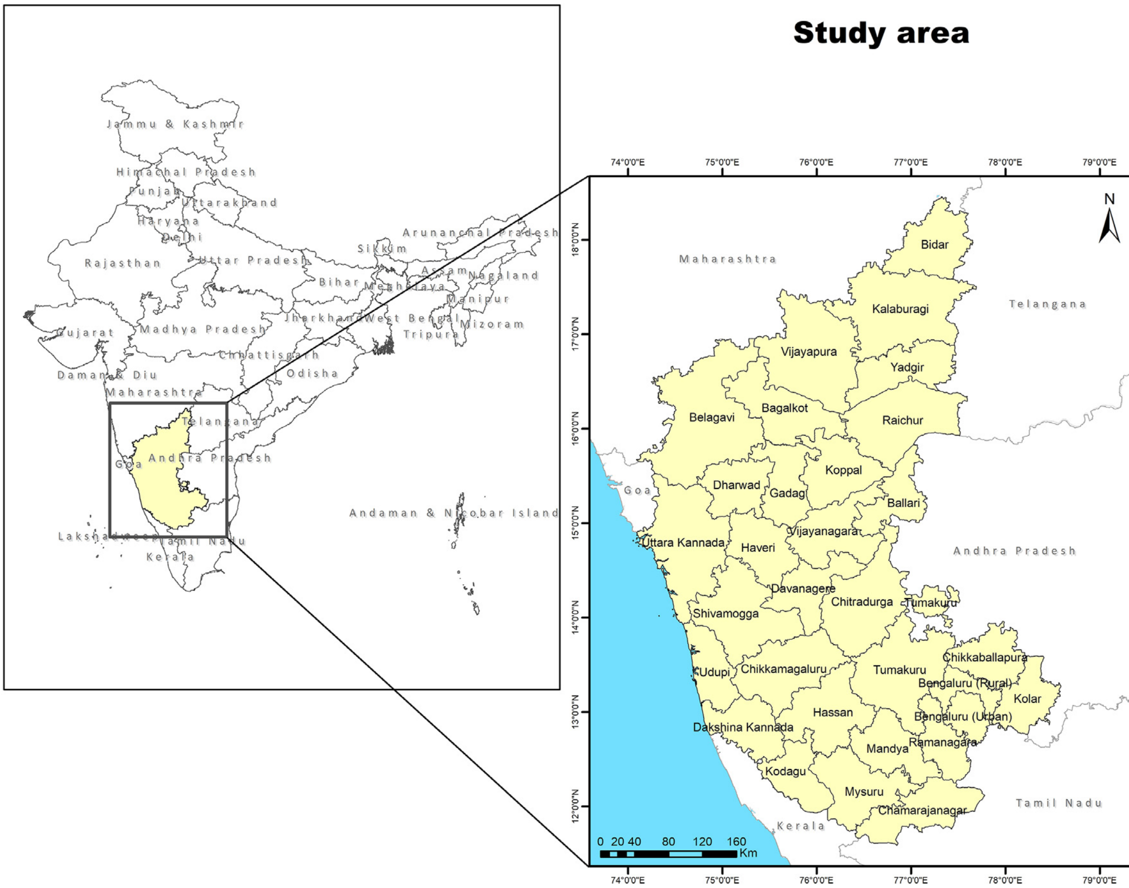

Fig. 1. Map representing the study area.

immediately evident, leading to a delayed perception of extreme heat as a life-threatening hazard [9]. However, the health risks posed by heatwaves are significant [10]. According to the Center for Disease Control and Prevention, heatwaves can exacerbate environmental issues and increase the risks of heat-related disorders, affecting human health both directly and indirectly. Some common heat-related medical conditions include heat rash, heat cramps, heat exhaustion, heat oedema, and heat syncope [1,11]. Heat can influence human behavior, disease transmission, air quality, healthcare delivery, and critical social infrastructure including energy, water, and transportation [12]. Heat-related health impacts are determined by the timing, duration, and severity of a temperature event as well as the level of acclimatization and adaptation of infrastructure, local residents, and institutions to the surrounding environment [13].

Rising climatic extremes also disproportionately affect developing countries with a higher prevalence of poverty, increasing the risk of infectious disease outbreaks [14]. Climate risks pose a greater threat to demographically vulnerable populations, including the elderly, women, and children [15−19]. Thus, it is critical to establish adequate techniques for identifying such hazards and vulnerable locations to analyze possible implications on human health [20,21].

Despite numerous studies on heatwave health risks in various parts of the world [22−24], research within India, specifically in the state of Karnataka, remains limited and there is a significant knowledge gap concerning the specific public health-related impacts of heatwaves. Local-level assessments to identify areas with greater heat risks are crucial for implementing effective mitigation and adaptation measures [23,24]. Thus, this study aimed to quantify the overall health risks associated with heatwaves in specific local areas in Karnataka. The main objectives were as follows: i) assessment of district-specific exposure and vulnerability to heatwave hazards under the current climate scenarios and ii) development and mapping of an overall heatwave health risk index (HHRI) for all districts in Karnataka.

2. Materials and methods

2.1. Study area

Located along the western coast of India, Karnataka state shares its borders with Goa, Maharashtra, Telangana, Tamil Nadu, and Kerala and has 31 administrative districts (Fig. 1). Karnataka has a subtropical climate with four distinct seasons: winter, summer, post-monsoon, and southwest monsoon. The annual rainfall varies from approximately 20 inches to 160 inches, with the primary monsoon period spanning the months of June−September. Additionally, a less pronounced northeast monsoon contributes to post-monsoon precipitation; however, winters tend to be dry in the state [25]. In recent decades, a significant change in temperature in the state has been observed [26] with the summer maximum temperature increased by 95% from 1951 to 2010 [27]. Moreover, Karnataka is overall prone to heatwaves, with 15 out of 31 districts being very highly prone [28].

2.2. Risk assessment

This study considered the risk assessment framework suggested by IPCC's Fifth Assessment Report [29], which introduces a climate change risk impact framework comprising three components: hazard, exposure, and vulnerability. According to the report, 'Hazard' refers to the potential occurrence of a natural or human-induced physical event or a trend of physical impact that may cause adverse impacts, including loss of life, injury, or other health impacts as well as damage and loss of property, livelihoods, service provisions, infrastructure, ecosystems, and environmental resources. 'Exposure'

Table 1
Indicators included in the study, their rationale for risk assessment, and the data sources.

Framework		Indicator	Rationale	Data source
Hazard		Heatwave occurrence	It helps represent the likelihood and severity of heatwaves occurring in a district.	India Meteorological Department Gridded Data (1985–2022)
		Diurnal temperature range	It provides a measure of variability of temperatures and can be an important predictor of heat-related mortality [30].	MODIS (MOD11A1) (2016–2022)
Exposure		Population density	It can affect the extent of exposure of a community to the impact of heatwaves. Regions with a substantial population density may have higher levels of exposure owing to the concentration of people and infrastructure [31].	Census (2011)
		Outdoor labor population (agricultural and construction workers)	Outdoor workers face an increased possibility of environmental heat exposure, given that a significant portion of the workforce engages in agricultural activities, functioning as cultivators and laborers within the agricultural sector [32].	
		Population travelling to their workplaces on foot	Workers primarily commuting to their workplaces on foot face increased heat exposure [33].	
Vulnerability	**Adaptive Capacity**	Number of medical institutions	Areas with limited access to healthcare facilities may face challenges in providing timely medical care to affected individuals, which can exacerbate the health risks associated with heatwaves [34].	Karnataka Economic Survey (2022–2023)
		Green cover (normalized difference vegetation index)	Numerous studies confirm the protective effect of green covers against heat-related mortality and heat island effects [35–37].	Sentinel-2A (2016–2023)
	Sensitivity	Elderly population > 60 years	The ability to regulate body temperature is weakened with ageing, making older individuals more sensitive to heat stress [38].	Census (2011)
		People with disabilities	Individuals with disabilities are considered more vulnerable than the general population because of their limited mobility and reduced capacity to respond to the surroundings, emphasizing their crucial inclusion [39,40].	
		Multidimensional poverty index	It is a comprehensive measure of poverty that looks beyond income and captures various inadequacies in education, health, and living standards. It includes indicators such as malnutrition, lack of education, poor health, inadequate housing, and lack of basic amenities and can help identify vulnerable populations who may have limited resources to cope with the impacts of heatwaves, such as those without electricity or safe access to drinking water [41].	Karnataka Human Development Index (HDI) report (2022)
		Health index	It incorporates indicators such as children with anemia, wasting, and stunting and children who are underweight. Pregnant women and individuals with chronic diseases (respiratory diseases, cardiovascular diseases, and tuberculosis) face a greater heat risk because of their potential physiological impairments, making them more vulnerable to sustained heat [42,43].	Karnataka HDI report (2022) and District-Level Household and Facility Survey (DLHS)–4

pertains to the presence of people, livelihood, infrastructure, ecosystems, services and resources, environmental functions, and cultural assets in areas susceptible to adverse effects. ‘Vulnerability’ is conceptualized as an internal property of a system and defined as the propensity or predisposition of a system to be adversely affected [15].

Indicators for each determinant were selected to provide measurable parameters for different components of the risk assessment framework. Both primary and secondary data were used in this study. Table 1 delineates these indicators and their rationale for risk assessment.

IMD daily temperature data were used to compute the heatwave occurrences. For the analysis, gridded maximum temperature data from the IMD with a 1°x1° resolution was used. Data for Karnataka was extracted, focusing on IMD’s heat wave criteria, which define a heat wave as when the maximum temperature reaches specific points for two days as noted in the introduction. Grid boundaries within districts were established based on the state’s topography: 37°C for coastal districts like Udupi and Dakshina Kannada, 35°C for hilly districts like Kodagu and parts of Belagavi, and 40°C for plains in the remaining districts [7].

The diurnal temperature range (DTR) and normalized difference vegetation index (NDVI) were extracted from satellite images using Google Earth Engine [44]. Furthermore, data from the Census of India 2011, the Karnataka Human Development Index report, the Karnataka Economic Survey (2022–2023), and the District-Level Household and Facility Survey (DLHS-4) were used as demographic-based variables for the exposure and vulnerability components of the research (Table 1). The Health index (HI)[1] used in this study was retrieved from the Human Development Index (HDI) report developed by the Planning, Programming Monitoring, and Statistics Department of the Government of Karnataka (Table 2) [45]. The multidimensional poverty index (MPI) from the HDI report was used in this study to measure non-income-based dimensions of poverty, providing a more comprehensive assessment of poverty and deprivation

[1] The term ‘health index’ used in the context of this study pertains to the proportion of population that is susceptible to heat impacts owing to their health condition

Table 2
Indicators included in the health index (HI) and their respective data sources.

		Data source	Indicators
Computation of health index (HI) in the current study	Health index	Karnataka Human Development Index (HDI) report, 2022	Number of children (6 months–6 years) Number of children who are underweight (0–5years) Number of children with anemia (0–5 years) Pregnant women with anemia (%) Adolescent girls with anemia (%) Adolescent girls who were underweight (%)
	Individuals with chronic diseases (%)	District-Level Household and Facility Survey (DLHS)-4	Reported prevalence of chronic illnesses during the last 1 year (%): Respiratory disorders Reported prevalence of chronic illnesses during the last 1 year (%): Cardiovascular disorders Reported prevalence of chronic illnesses during the last 1 year (%): Tuberculosis

[41]. The specific indicators used to compute the MPI are mentioned in *Supplementary Table 1*.

To calculate the HHRI, individual indices were developed for each determinant of risk, namely hazard (H), exposure (E), and vulnerability (V) using IPCC methodology through standardization, normalization and aggregation. Finally, HHRI was then calculated using Eq. (1) [46].

$$HHRI = \sqrt[3]{H * E * V} \quad (1)$$

Subsequently, individual ranks were assigned to each district based on their respective HHRI values, enabling a relative assessment of heatwave health risks across the study area. Then are categorized in to very high', 'high', 'moderate', 'low', and 'very low' categories and spatially mapped using ArcGIS.

3. Results

This section is structured into two segments: the first part reviews the risk indices for all hazard, exposure, and vulnerability components and the second part focusses on the overall risk index.

3.1. Indices for risk components

3.1.1. Hazard index

Analysis of the temperature data under heatwave conditions and DTR, revealed significant findings. Results indicate varying occurrences of heatwave days (1985−2022) across Karnataka's 31 districts. The northern and central districts (Bidar, Kalaburagi, Yadgir, Raichur, Gadag, Dharwad, Koppal, Ballari, Bagalkot, Vijayapura, Vijayanagara, and Chitradurga) experienced a higher number of heatwave days, ranging from 91 to 187 total days (during a period of 37 years) (*Supplementary Figure 1(a))*. Furthermore, *Supplementary Figure 1(b)* highlights that Bidar, Kalaburagi, Vijayapura, Dharwad, and Gadag experienced the highest DTR, reaching as high as 17.9°C in Bidar, indicating a substantial difference between daytime and nighttime temperatures. Conversely, Uttara Kannada, Udupi, Dakshina Kannada, and Kodagu recorded the lowest DTR occurrences in Karnataka, with Dakshina Kannada having the lowest value at 7.9°C.

An overall spatial representation of the hazard index values across each district is presented in Fig. 2, with values ranging from 0 to 1. The category with a 'very high' hazard value comprised six districts. Among these, Bidar stood out as the most susceptible district to heatwaves in Karnataka (1) followed by Kalaburagi (0.972), Gadag (0.842) and Yadgir (0.80), Vijayapura (0.79), and Raichur (0.78) districts. Koppal, Dharwad, Vijayanagara, Ballari, Chitradurga, and Bagalkot districts which range between 0.45 and 0.7 are denoted as high hazard districts. Five districts, namely Devanagere, Haveri, Belagavi, Chikkaballapura, and Tumakuru, were moderately prone to heatwaves, with hazard index values ranging from 0.45 to 0.3. Southern districts such as Kolar, Bengaluru (Urban), Hassan, Mysuru, Shivamogga, Chamarajanagar, Bengaluru (Rural), Mandya, Uttara Kannada, Chikkamagaluru, and Ramanagara are low hazard districts (0.3 to 0.06). Kodagu and the coastal districts of Udupi and Dakshina Kannada were found to be the least prone to heatwaves. In general, the data suggested that districts in northern Karnataka exhibited a higher susceptibility to heatwaves than those in the southern regions.

3.1.2. Exposure index

Supplementary Figure 2 displays individual maps for visualizing indicators contributing to the exposure index and Fig. 3 depicts the overall exposure index for heatwaves in each district. Among the districts in Karnataka, Dharwad and Bengaluru (Rural) fall into the highest-exposure category, with exposure index values of 0.83 and 0.73, respectively. The high-exposure category includes: Bengaluru (Urban), Dakshina Kannada, Mysuru, Kalaburagi, Udupi, Kolar, and Bidar (0.7 to 0.57). Mysuru and Bengaluru (Urban) exhibited high values attributed to their higher population densities. Conversely, Kalaburagi, despite having a low population density, was classified in the high-exposure category because of its substantial outdoor labor population and a significant number of individuals commuting to their workplaces on foot. Similarly, Udupi, with a moderate population density, was categorized as highly exposed because of a considerable population commuting to their workplaces on foot.

The moderately exposed districts are Haveri, Devanagere, Vijayanagara, Ballari, Bagalkot, Shivamogga, Gadag, Raichur, and Koppal (0.57 to 0.5). Chikkamagaluru, Yadgir, Chikkaballapura, Uttara Kannada, Belagavi, Ramanagara, and Vijayapura districts have low exposure. Lastly, six southern districts Chamarajanagar, Chitradurga, Hassan, Mandya, Kodagu, and Tumakuru fall under lowest-exposure category.

3.1.3. Vulnerability index

Vulnerability index includes the sensitivity and adaptive capacity of the people to heat hazards. *Supplementary Figure 3* illustrates indicators enhancing adaptive capacity as a component in the vulnerability index; *Supplementary Figure 4* illustrates indicators contributing to the susceptibility component of the overall vulnerability and Fig. 4 displays the overall vulnerability index for each district. Bidar is the most vulnerable district because of poor green cover and limited medical infrastructure, resulting in an overall decrease in its adaptive capacity. Additionally, Bidar showed a high number of people with disabilities and ranked high on the HI, rendering the population more susceptible to heatwaves.

The high-vulnerability category comprised 10 districts: Kalaburagi, Gadag, Koppal, Haveri, Yadgir, Belagavi, Mandya, Tumakuru, Mysuru, and Raichur. Kalaburagi and Gadag districts exhibited similar vulnerabilities to Bidar, albeit with a lower HI ranking, indicating

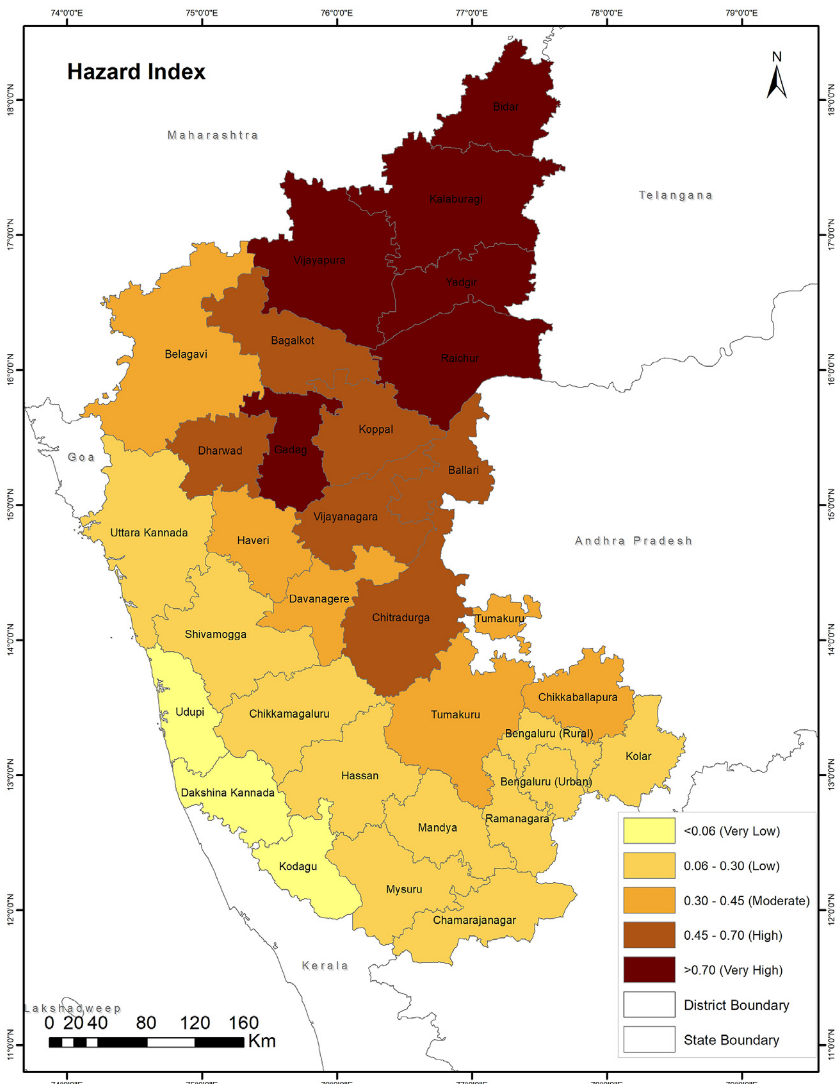

Fig. 2. Map illustrating hazard index distribution across Karnataka districts.

the presence of a healthier population in these districts. However, Belagavi's categorization as a highly vulnerable district can be attributed to its highest HI value, signifying a population with numerous health-related issues, consequently elevating its overall susceptibility to heatwaves. In addition, Mandya and Tumakuru were categorized as highly vulnerable districts owing to their significant elderly populations (>60 years). Conversely, despite Raichur's low elderly population, its high MPI and HI rankings increase its susceptibility to heatwaves.

Vijayapura, Chikkaballapura, Chitradurga, Chamarajanagar, Ballari, Bagalkot, Chikkamagaluru, Bengaluru (Rural), and Ramanagara are moderately vulnerable. Among these districts, Chikkamagaluru had the highest adaptive capacity because of its lowest population burden on medical institutions and a high green cover. The low-vulnerability category included Kolar, Davangere, Uttara Kannada, Dharwad, Bengaluru (Urban), Hassan, Vijayanagara, Udupi, Kodagu, and Shivamogga. Lastly, Dakshina Kannada was categorized as the lowest vulnerable district. Six districts from the 'low vulnerability' and 'lowest vulnerability' categories (Uttara Kannada, Udupi, Hassan, Dakshina Kannada, Shivamogga, and Kodagu) lie in the Western Ghats belt, thereby exhibiting high green cover and consequently enhanced overall adaptive capacities. Udupi had the highest elderly population, which was offset by its lowest HI value and the number of people with disabilities. Of note, Dharwad, despite its low green cover and adaptive capacity, qualified as a low vulnerability district, primarily because of its low MPI values, signifying low poverty.

3.2. Risk analysis

The risk index developed in this study highlighted Bidar district in northern Karnataka and Kodagu district in southern Karnataka as the most and least risk-prone districts of Karnataka, respectively (Fig. 5). An important observation from Figs. 5 and 6 was that all northern districts in Karnataka were characterized as 'very high risk' to 'high risk', except for Belagavi, which was categorized as 'moderate risk'. This implies that nearly 40% of the state (13 out of 31 districts) faces health risks due to heatwaves. Approximately 25% of the state (8 districts) was categorized as 'moderate risk', and around 30% (10 districts) as 'low' to 'very low' risk. Notably, Dakshina Kannada and Kodagu were the only districts categorized as 'very low risk'.

The highest-risk category comprised four districts from northern Karnataka, including Bidar, Kalaburagi, Gadag, and Dharwad. Bidar's classification as the most risk-prone district in Karnataka could be attributed to its highest hazard index and categorization as a 'high exposure' and 'very high vulnerability' district. Kalaburagi was the second-most risk-prone district. Although Gadag was classified as a

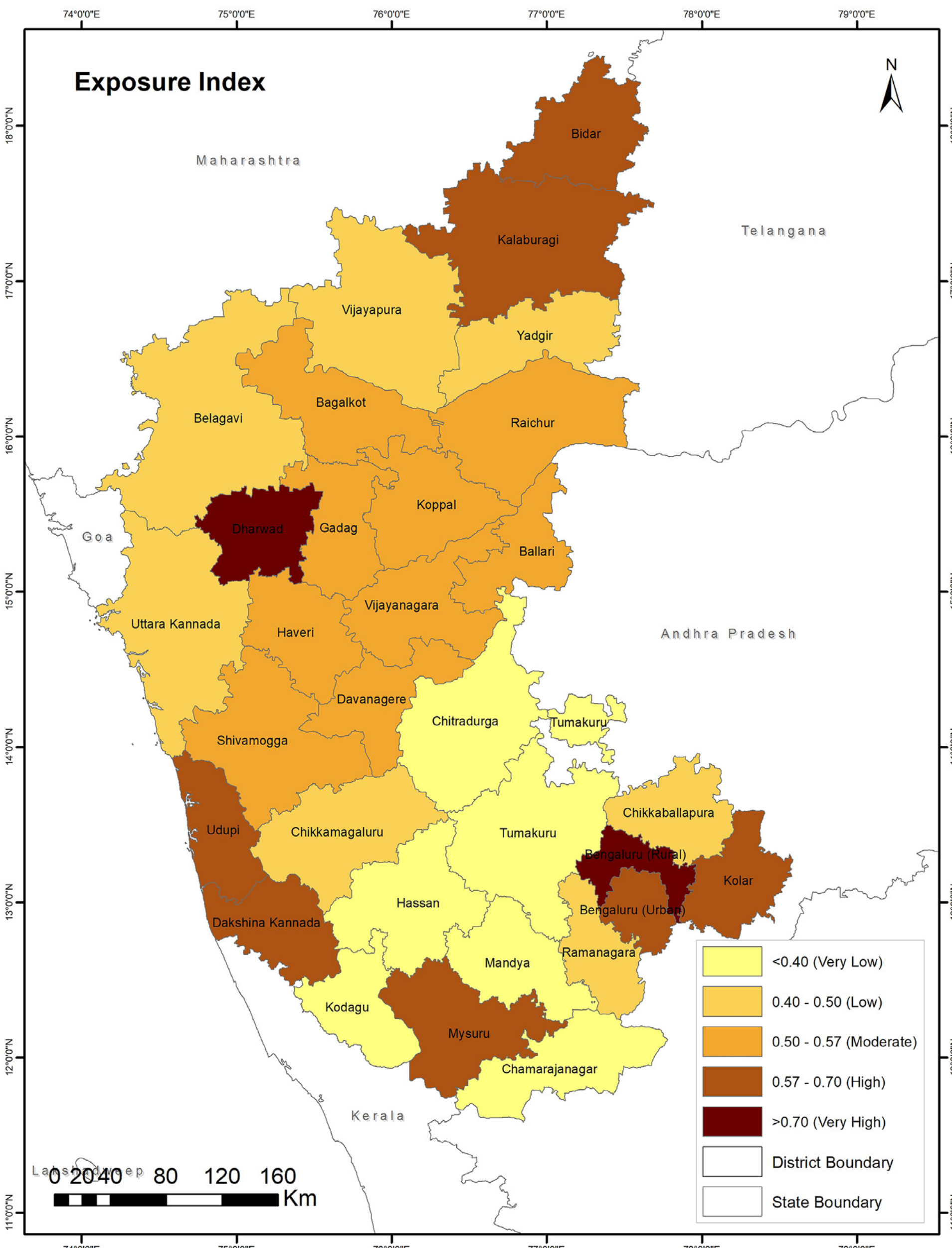

Fig. 3. Map illustrating exposure index distribution across Karnataka districts.

'moderately exposed' district, it ranked among the top four most risk-prone districts owing to its categorization as one of the highest hazard-prone and vulnerable districts. Similarly, Dharwad's categorization as a 'high hazard' and the 'highest exposure' district offsets its classification as a 'low vulnerability' district, thereby placing it among the top four most risk-prone districts.

The high-risk category comprised Yadgir, Raichur, Koppal, Ballari, Vijayapura, Bagalkot, Vijayanagara, Haveri, and Chitradurga. Among these, Yadgir and Raichur were categorized as the highest hazard-prone districts; the remaining districts (except Haveri) were classified as high hazard districts and were documented to experience the highest number of heatwave days. Furthermore, a majority of these districts exhibited high rankings in either the exposure index or vulnerability index.

The moderate-risk category comprised Belagavi, Devanagere, Bengaluru (Urban), Kolar, Mysuru, Chikkaballapura, Bengaluru (Rural), and Tumakuru. The low-risk category comprised eight districts located in southern Karnataka: Chikkamagaluru, Chamarajanagar, Shivamogga, Ramanagara, Uttara Kannada, Hassan, Mandya, and Udupi. Lastly, two districts were included in the lowest-risk category: Dakshina Kannada and Kodagu. Kodagu was ranked as the least-risk district owing to its lowest values across all three indices: hazard, exposure, and vulnerability.

4. Discussion

Our study aligns with existing research, demonstrating consistency in findings. However, it is important to acknowledge that comparing vulnerability across studies can be challenging, as differences in the indicators used may influence the results. Despite these variations, our overall findings are consistent with some existing research. For instance a recent study by Mandvikar et al. on the Heat Health Risk Index (HHRI) across 37 Indian cities using geospatial and socio ecological data indicates Bengaluru is one of the lowest heat vulnerabilities in a nationwide analysis [47]. This finding aligns with our district-level research, where Bengaluru ranks in the extremely low

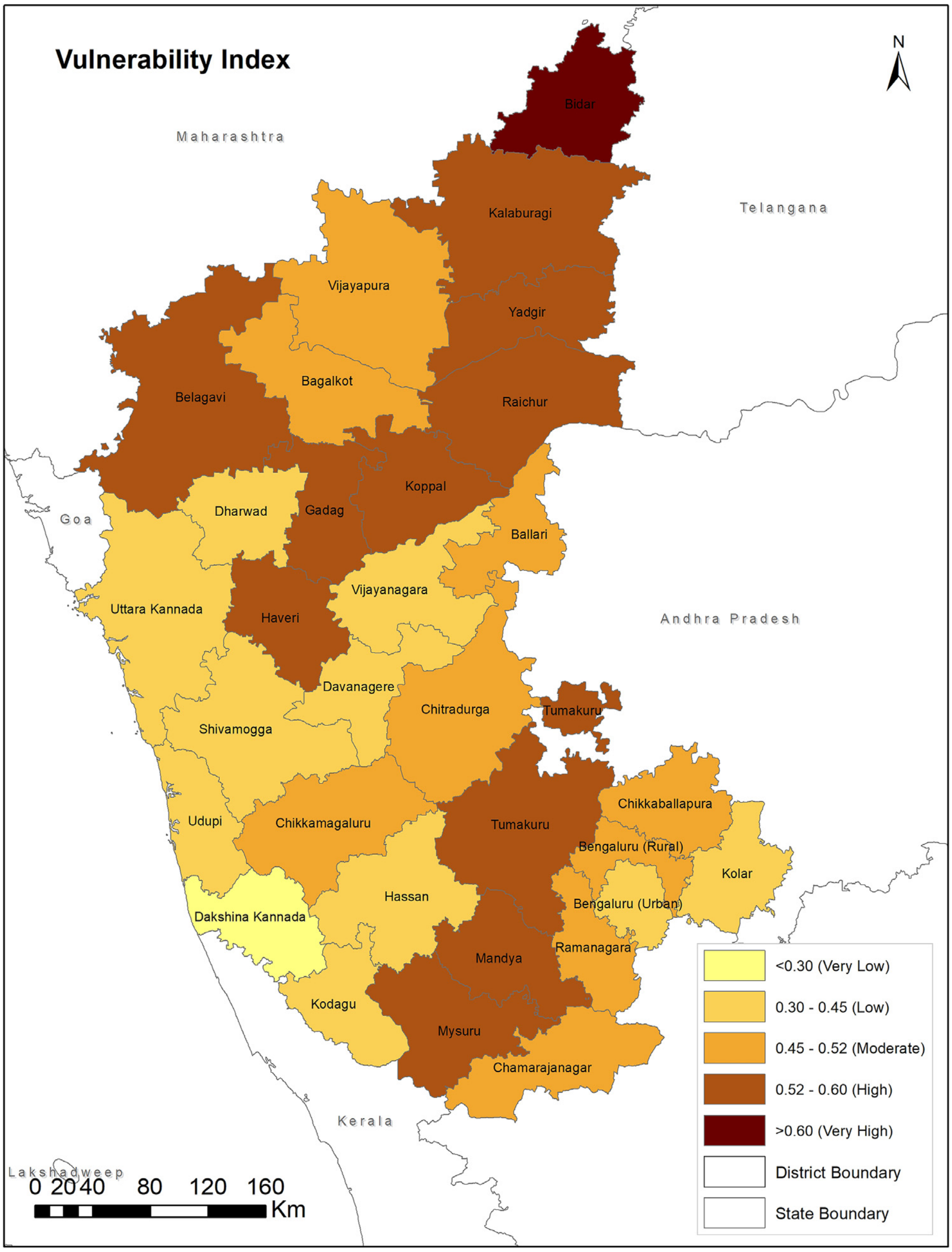

Fig. 4. Map illustrating vulnerability index distribution across Karnataka districts.

vulnerability category, attributing to the fact that it has good amount of green cover. The study on climate vulnerability assessment for Karnataka state by Kumar et al. (2021), indicates Bidar and Gulbarga are the most prone and susceptible districts to climate change whereas Dakshin Kannada is the least vulnerable district in the State [48]. These findings corroborate our results, suggesting robustness and consistency in the identified patterns of vulnerability.

Limitations of our study is that this study uses 2011 census data, which was the most recent and comprehensive population dataset available at the time of analysis, thus it might not fully reflect evolving nuances of health risks, especially given subsequent population growth. Using the forthcoming updated census data will reflect the current scenario and is warranted. Additionally, enhancing the study with additional indicators, such as access to cooling facilities, and expanding the focus to include the relationship between heatwaves and infectious disease outbreaks, will further improve the relevance and adaptability of future analyses.

Additionally, in order to provide specific policy recommendations, it is crucial to comprehend the key factors driving risks. The drivers of risk across various risk classes in our study were represented by the averages of their normalized indicator values. Indicators falling within the normalized score range of 0.6–0.7 were identified as noteworthy risk contributors, whereas those surpassing the score of 0.7 were identified as the primary risk drivers (highlighted in bold), as presented in Table 3.

The ‘very high risk’ category could be attributed to several key drivers including high DTR, which increases the likelihood of hazard occurrences; limited green cover, which reduces the adaptive capacity in the event of hazard exposure; a high proportion of the population working outdoors, which leads to an increased overall exposure to heatwaves; and a significantly high number of people with disabilities, increasing sensitivity to heatwaves.

Similarly, for subsequent risk classes, the key drivers are outlined in Table 3 as derived from Fig. 7. These drivers of risk should be the

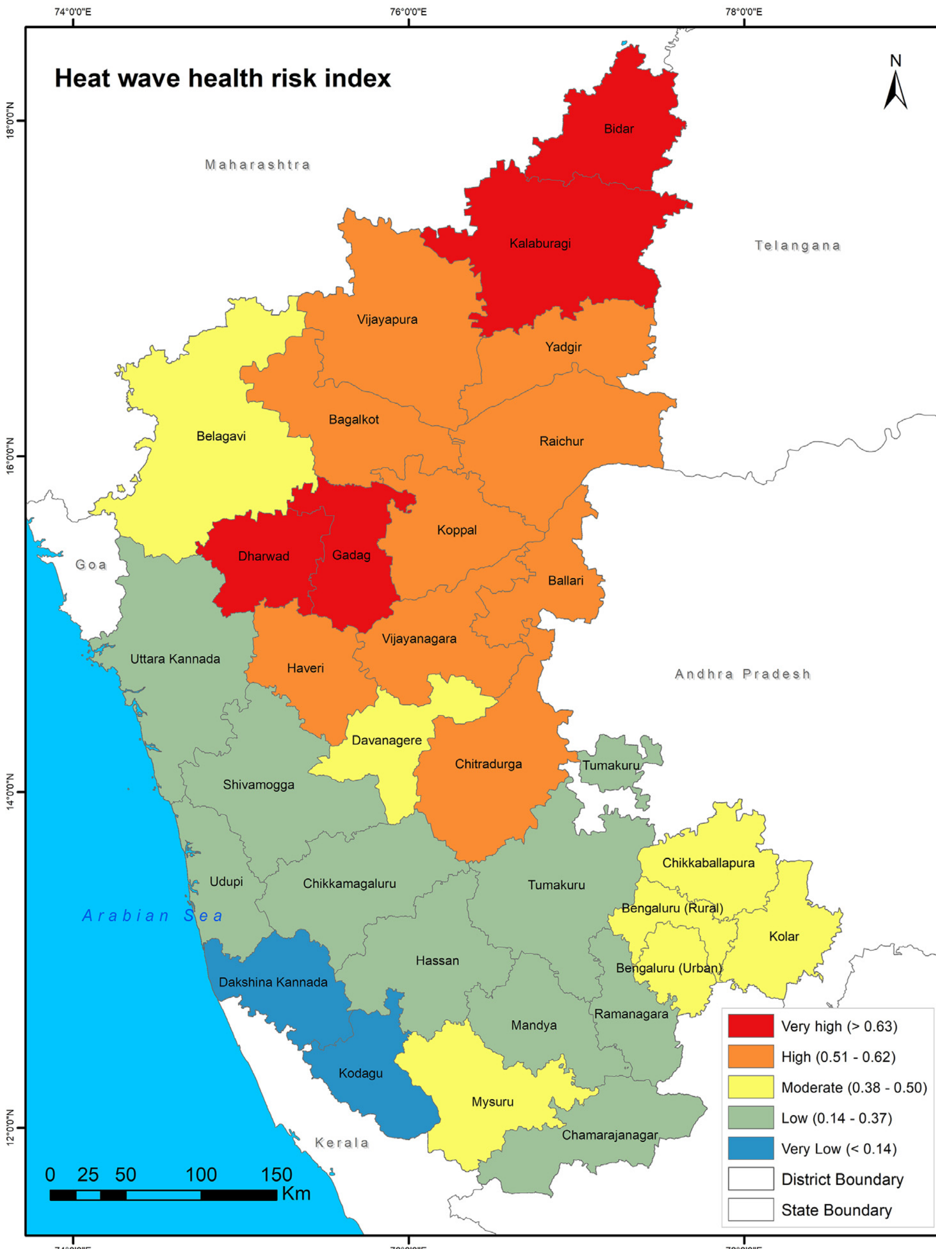

Fig. 5. Risk index mapping of Karnataka districts.

focal points for the development of new policy recommendations aimed at enhancing the adaptive capacity of these districts and reducing the vulnerability of sensitive populations.

These drivers necessitate policy interventions and immediate solutions. The state/district policies should prioritize green cover enhancement to bolster adaptive capacity. Additionally, districts with a high proportion of elderly individuals or people with disabilities should formulate policies to support these vulnerable groups, thereby reducing heatwave-related health risks. Lastly, policies aimed at alleviating the strain on healthcare facilities should be a priority to enhance the overall adaptive capacity.

Districts characterized by high growth rates and population densities typically exhibit greater exposure, whereas those with negative or slow growth rates and lower population densities tend to display lower exposure indices. Districts with a significant number of urban centers, which serve as financial hubs and draw in populations, face heightened exposure owing to population growth and increased urbanization. Hence, the government should implement specialized programs targeting districts with high exposure and risk indices [49].

In this study, Bidar, Kalaburagi, and Gadag were classified among the most vulnerable districts. Therefore, addressing the diverse vulnerabilities of this region necessitates immediate special attention. As per the Karnataka Economic Survey (2021–22), a significant portion of the workforce in this area (approximately 68% of the total workforce) is engaged in the agricultural sector. Hence, it is imperative for the state government to develop strategies aimed at increasing employment and educational opportunities within the vulnerable districts of Karnataka. This could involve diversifying income sources beyond agriculture [46].

The decision-making process regarding commonly advocated practices such as the use of air conditioners and access to cooling centers is very complex, with barriers including financial, physical, or cultural inaccessibility [50]. Thus, as recommended by Azhar et al. [32], it is crucial to implement suitable local adaptation measures for

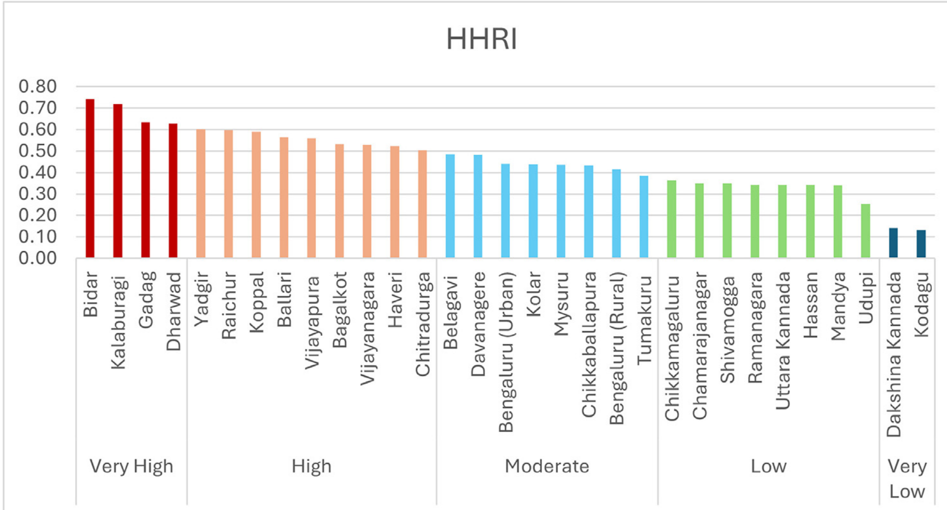

Fig. 6. Graphical representation of the risk mapping of Karnataka districts.

Table 3
Drivers of health risk due to heatwaves in Karnataka.

Risk class	Districts	Drivers of risk
Very high risk	Bidar, Kalaburagi, Dharwad, and Gadag	1. High diurnal temperature range (DTR) 2. Poor green cover 3. High proportion of population working outdoors 4. High heatwave occurrence 5. High number of people with disabilities 6. High proportion of individuals travelling to their workplaces on foot
High risk	Vijayapura, Yadgir, Bagalkot, Raichur, Koppal, Haveri, Vijayanagar, Ballari, and Chitradurga	1. High proportion of population working outdoors 2. Poor green cover 3. High DTR 4. High number of people with disabilities 5. High heatwave occurrence
Moderate risk	Belagavi, Davangere, Mysuru, Tumakuru, Chikkaballapura, Kolar, Bengaluru (Urban), and Bengaluru (Rural)	1. Poor green cover 2. High population density 3. High number of people with disabilities
Low risk	Uttara Kannada, Shivamogga, Udupi, Chikkamagaluru, Hasan, Mandya, Ramanagara, and Chamarajanagar	1. Poor green cover 2. High population burden on medical institutions 3. High elderly population (age > 60 years) 4. High proportion of individuals travelling to their workplaces on foot
Very low risk	Dakshina Kannada and Kodagu	1. High proportion of individuals travelling to their workplaces on foot 2. High population burden on medical institutions 3. Poor green cover

coping with heatwaves, such as disseminating public messages (through radio and television), issuing mobile-based alerts, and encouraging practices like remaining indoors. Important adaptation techniques include housing design elements such as insulating materials, shaded windows, and underground water storage tanks, which contribute significantly to preventative measures against heatwave impacts. Integral aspects of housing, such as indoor toilets and the availability of drinking water, represent essential components of adaptation strategies. These findings illuminate the regional disparities in health-risk levels throughout Karnataka, offering crucial data for policymakers and stakeholders to prioritize and execute tailored interventions aimed at effectively reducing heatwave-related health risks.

5. Conclusions

In this study, hazard, exposure, and vulnerability indices were generated and subsequently amalgamated to calculate the HHRI for each district of Karnataka. Bidar, Raichur, Gadag, and Dharwad districts require immediate and focused attention for heatwave risk mitigation. Consequently, districts with high-to-very high HHRI values necessitate policies to promote strategies focusing on adaptation to reduce sensitivity. The state's Heatwave Action Plan intends to coordinate efforts among departments and communities to protect against preventable health concerns during periods of extreme heat [28]. Simultaneously, directing greater attention towards short- and medium-term adaptation strategies should be the primary emphasis of disaster preparedness efforts by the state government. Disaster preparedness entails a range of actions including early warning dissemination to remote areas, conducting mock drills and emergency operations, medical preparedness, fostering community awareness, and system enhancement [51].

Given the escalating climate change impacts, our findings highlighted hotspot districts where interventions should be concentrated. Our study also intended to help the authorities, early warning agencies, and communities to identify the risk and its interlinkages with exposure, adaptive capacity, and sensitivity to mitigate the impacts of heatwaves. For instance, promoting green spaces and improving medical facilities can enhance the resilience of vulnerable districts.

To reduce the overall heat health risk in the state, policies aimed at supporting climate-resilient livelihoods and occupational safety

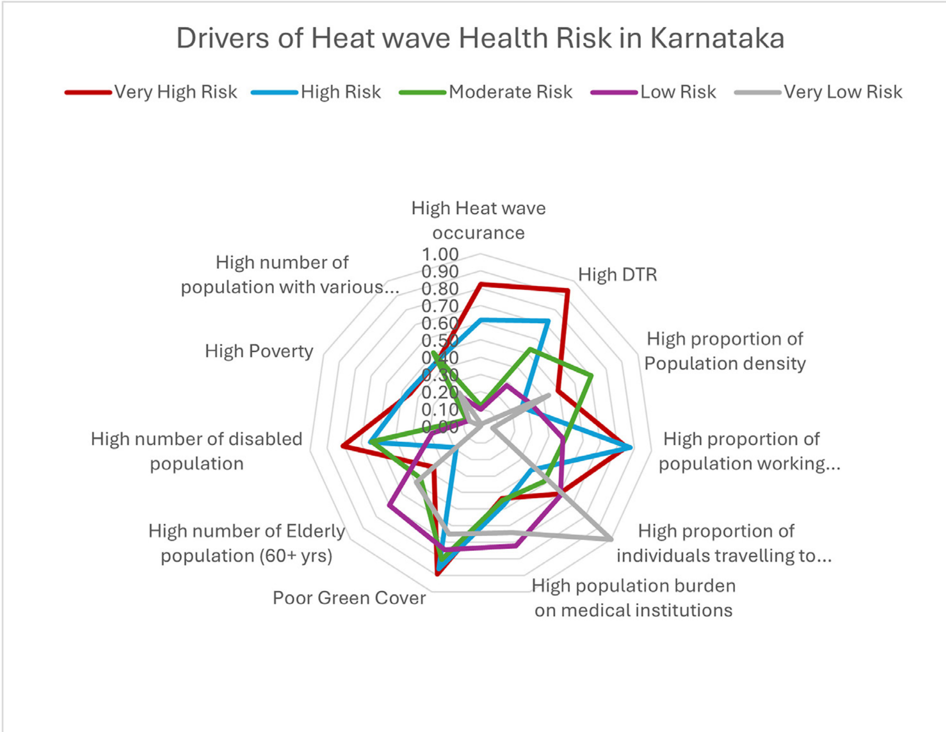

Fig. 7. Drivers of heatwave health risk in Karnataka districts.

measures, particularly for outdoor workers, will further lower sensitivity to heatwaves. Additionally, ensuring better data collection and monitoring will help fine-tune these efforts and make the HHRI more adaptive to local needs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Vidhatri Thakkar: Writing – original draft, Formal analysis, Data curation. **Vidya Srinivas:** Software, Formal analysis, Data curation. **Pradeep Marula Siddhappanavara:** Software, Formal analysis, Data curation. **Tashina Madappa:** Formal analysis. **Anushiya Jeganathan:** Writing – review & editing, Supervision, Project administration, Investigation, Conceptualization. **Indu K. Murthy:** Writing – review & editing.

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Data Availability

The datasets generated during and analyzed during the current study are available from the corresponding author on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version at doi:10.1016/j.joclim.2025.100428.

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