Assessing climate change impacts on heat waves and heat index: a case study of Uttar Pradesh, India
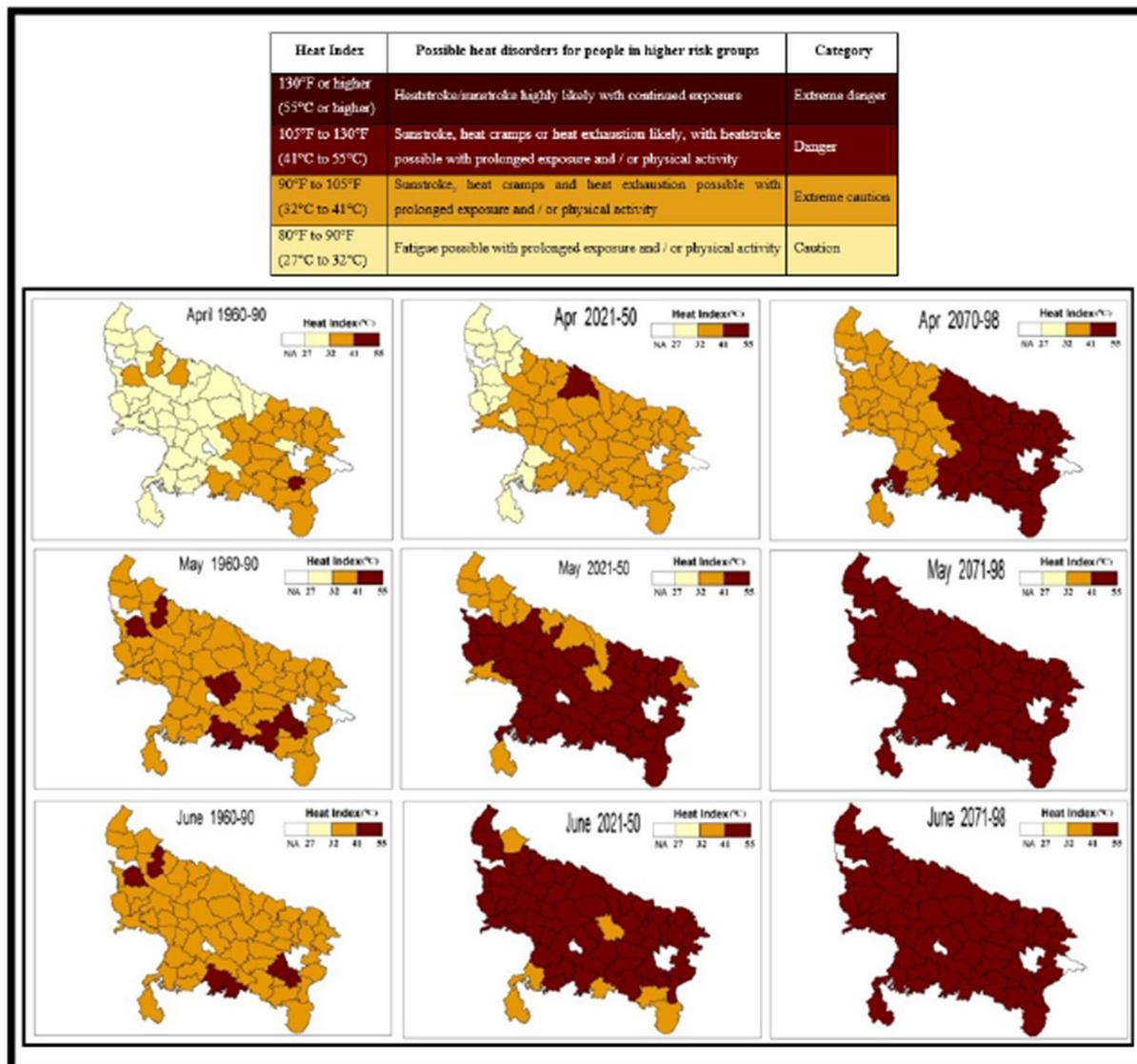
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Extreme environmental events such as Heat Waves (HWs), cold waves, and droughts intensified by climate change are increasingly associated with adverse health outcomes. In this study, investigation of the extreme temperature across Uttar Pradesh (U. P.), one of India's largest and densely populate states has been done. Using high-resolution climate data from the Providing REgional Climates for Impacts Studies (PRECIS) model, including maximum temperature (T_{max}), minimum temperature (T_{min}), and Relative Humidity (RH) were systematically extracted for different districts of U. P. Heat Index (HI) and HW were then calculated for three distinct periods: 1961–1990 (base century), 2021–2050 (mid-century), 2071–2098 (end-century), respectively under the A1B scenario. Results show a clear intensification of extreme temperature conditions, with several districts expected to experience extensive, more frequent, and more severe HW and HI events in future climate scenarios. Based on HI, it is observed that nearly all districts of U. P. are likely to end up in the danger zone especially during May and June months. Districts like Gazipur, Jaunpur, Varanasi, and Chandauli are more impacted by heat as they show higher HI values, a greater number of HW days, and stronger deviations in temperature extremes, which together indicate growing risks of extreme thermal discomfort. The intended audience for this research includes climate scientists, public health authorities, disaster-risk planners, and local government agencies. Researchers working on regional climate impacts can apply these insights to strengthen future heat-risk assessments. Overall, this study provides a scientific foundation for targeted heat-risk mitigation in U. P. and emphasizes the urgent need for localized adaptation strategies to safeguard communities against intensifying extreme heat. These findings also contribute to the global understanding of extreme heat resilience in a warming world.

Heat Index	Possible heat disorders for people in higher risk groups	Category
130°F or higher (55°C or higher)	Heatstroke/sunstroke highly likely with continued exposure	Extreme danger
105°F to 130°F (41°C to 55°C)	Sunstroke, heat cramps or heat exhaustion likely, with heatstroke possible with prolonged exposure and / or physical activity	Danger
90°F to 105°F (32°C to 41°C)	Sunstroke, heat cramps and heat exhaustion possible with prolonged exposure and / or physical activity	Extreme caution
80°F to 90°F (27°C to 32°C)	Fatigue possible with prolonged exposure and / or physical activity	Caution

GRAPHICAL ABSTRACT

1 Introduction

Rapid growth of industries and technological advancement emitted large amount of greenhouse gasses (GHGs) that alter the natural composition of the atmosphere that contribute the global warming and climate change. Several factors have contributed to GHGs, including industrial processes, vehicle emissions, open residue burning (Agarwal et al., 2014; Singh et al., 2010) and deforestation, which have led to global warming, thereby calling for changes in weather and precipitation patterns, receding ice caps, melting glaciers, changes in sea level, etc. (Pattnayak et al., 2023; Awasthi et al., 2022a). According to Intergovernmental Panel on Climate Change (IPCC) (2021) and World Meteorological Organization (WMO) (2023), technological and industrial expansion since the industrial revolution is one of the important reasons behind the environmental degradation and atmospheric imbalance. Because of different anthropogenic activities that

produce different types of atmospheric pollutants responsible for different extreme events like Heat Waves (HWs), cold waves, droughts, cyclones, etc. (Zittis et al., 2022). Among other factors, climate change is considered as a key factor responsible for extreme weather events, with high temperature identified as one of the deadliest hazards, establishing more risk in comparison to other hazards like flood etc., as reported by Weilnhammer et al. (2021).

The changes in the temperature trend in the last decades were detected by researchers globally (Awasthi et al., 2023; Twardosz et al., 2021). Increase in temperatures are not only a feature of some developed countries but are now commonly observed in developing countries because they occur as a result of global processes and are therefore a significant cause for concern among researchers (Wedler et al., 2023). Global-average surface temperature has risen by roughly 0.7 °C (and now over 1.0 °C) compared with early-20th-century levels, and projections suggest that the final decades of this century may see unprecedented higher levels of warming (Hansen et al., 2006;

Kaufman et al., 2020; NASA, 2023). Projections suggest that this trend will continue with a predicted rise ranging from 1.1 to 6 degrees Celsius, potentially reaching a 4-degree Celsius increase by the year 2,100 (IPCC, 2006).

The frequency of extreme events has increased over time, and HWs, once considered primarily a concern for developed nations, are now affecting many parts of the world, including developing regions (Kim and Kim, 2017). Heat waves have emerged as one of the most frequent and serious weather extremes in recent years, affecting people's health, urban sustainability, and socio-economic systems. According to the definition by World Meteorological Organization (WMO) (2023), a HW is a period of abnormally high temperatures compared to local climatology. As per the IPCC's report, that the intensity and frequency of HWs have increased substantially in different part of the world since the mid-20th century due to the rise in the concentration of different GHG (Intergovernmental Panel on Climate Change (IPCC), 2021).

Heat events, such as those in China (2022), North America (2021), and Europe (2003, 2019), have led to thousands of fatalities, crop losses, and infrastructure disruptions. The New York HW event of 1896 which was extended up to 10 days and responsible for deaths over 1,500 peoples (Petkova et al., 2014). The extreme HWs that occurred in other parts of the world, like the 1995 Chicago HW and the 2003 European HW, resulted in large number of fatalities, thereby increasing awareness among researchers on the realistic dangers due to the impact of HW (Kohn, 2010; Petkova et al., 2014). HWs are not limited to certain developed locations but are present across the globe and involve most of the countries, with an increase in intensity (Shahfahad et al., 2024b). These types of extensive events became a focal point of researchers and scientists' community and highlight the urgent need for climate resilience and adaptation strategies to mitigate the impacts of extreme heat on human health, food security, and urban infrastructure (Abbass et al., 2022; Abunyewah et al., 2025; Tchonkouang et al., 2024).

Because of geographical diversity and tropical location, India which is one of the emerging economies is vulnerable to rising temperature extremes (Arulalan et al., 2023; Dash et al., 2007; Murari et al., 2015). The IPCC AR6 reported that India as one of the global HW risk regions where both apparent temperature and wet-bulb temperature are projected to exceed human tolerance thresholds (Dash and Kjellstrom, 2011; Kumar et al., 2022). In general, there is no standard definition of HW as it depends upon the geographical conditions (Yadav et al., 2023). The India Meteorological Department (IMD) defines a heatwave as a condition where the maximum temperature exceeds 40 °C in the plains and is at least 4.5 °C above normal or when the actual maximum temperature is ≥45 °C for two consecutive days [India Meteorological Department (IMD), 2023]. For more details on the definition of heatwave follow the review paper by Awasthi et al. (2022b). Studies have shown that heatwave days in India increases and have tripled over the last five decades (Kumar and Chakraborty, 2025; Pai et al., 2013; Rohini et al., 2019), with the Indo-Gangetic Plains (IGP) emerging as a key hotspot (Krishnan et al., 2020).

Among different IGP states of India, states such as Rajasthan, Punjab, Haryana and Delhi experience frequent and intense heatwaves, Uttar Pradesh (U. P.) was selected for this study due to its unique combination of climatic exposure, population density, and socio-economic vulnerability. Geographically, U. P. located in the central part of Indo-Gangetic Plain, a transitional zone between the arid northwest and humid east, where the interaction of large-scale

circulation, land-surface feedback, and irrigation practices produces complex heatwave dynamics (Krishnan et al., 2020). U. P. experiences extreme pre-monsoon temperatures due to its continental climate, extensive agricultural activity, and rapid urbanization (Pattnayak et al., 2023). Moreover, U. P. is India's one of the most populous state (≈240 million) and contributes significantly to national agriculture and urban growth, making the human and economic exposure to heat stress exceptionally high (Pandey et al., 2024). Unlike the less populated desert areas of Rajasthan or the more developed states like Punjab and Haryana, many people in U. P. do not have enough access to cooling facilities, good healthcare, or proper infrastructure. This makes them more vulnerable and increases the risk of illness and death during periods of extreme heat (Rohini et al., 2019).

Despite these challenges, region-specific studies on heatwave dynamics and their future projections over U. P. remain inadequate. Limited region-specific projections exist for U. P., highlighting the need to generate high-resolution climate projections for this critical and densely inhabited part of northern India. Although HW in India are well recognized, limited studies have focused specifically on U. P., a densely populated, agricultural and socio-economically vulnerable state where the combined effects of climate change, rapid urbanization, and inadequate infrastructure significantly intensify the heat-related risks (Liyanage et al., 2024). Most previous studies have examined national or regional trends without detailed spatial assessment using regional climate models. This research gap is filled by analyzing heat wave frequency and heat index projections across multiple future time slices. Hence, this paper focuses to study the HW of the U. P. which is one of the most fertile and densely populated regions of the Indo-Gangetic Plain (IGP). Aim of study is to assess historical trends and future projections of temperature and heatwaves in U. P. using the Providing REgional Climates for Impact Studies (PRECIS) model, under base-century (1961–1990), mid-century (2021–2050) and end-century (2071–2098) scenarios. Along with the HW measurements, the effect of heat stress is considered by combining the temperature and humidity with help of the calculation of Heat Index (HI) for U. P. under the different time slices.

2 Materials and methods

2.1 Site under observation

The study is carried for all the districts of U. P., India, which lies between latitude 24° to 31°N and longitude 77° to 84°E. U. P. is geographically the fourth largest state in the country with population density making it the most populous state of India. Situated in the south west region of Indian peninsula, it occupies an area of only 44,447 square kilometer but has a population density of 828 people per square kilometer (Baliyan, 2016; Tiwari, 2015). Agriculture being the dominant sector of this state, majority of the population of U. P. based their income on this sector it contributing 41% of the state's gross domestic product (Tiwari, 2015). State U. P. comprising diverse agro-climatic zones ranging from the semi-arid Bundelkhand plateau in the south to the humid Terai belt in the north. U. P's geography and land-use pattern is characterized by dense settlements, extensive agriculture, and growing urban centers that make it highly sensitive to extreme temperature events and climate variability (Pandey et al., 2024). Historical records show that U. P. consistently ranks among the top five Indian states

FIGURE 1
Study region, Uttar Pradesh (U.P.), India (QGIS Development Team, 2024).
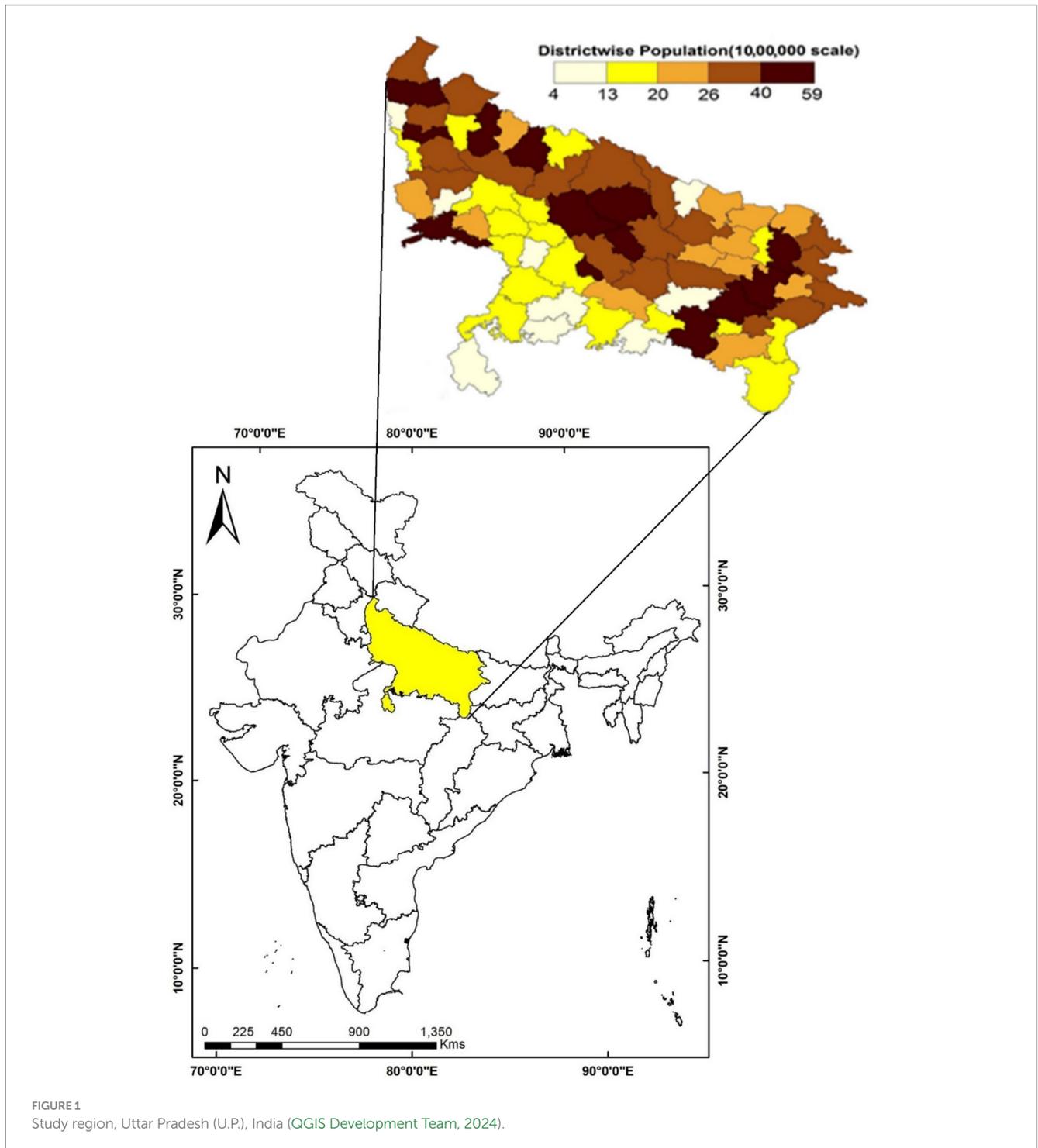
affected by heatwaves, with increasing intensity and duration in recent decades [India Meteorological Department (IMD), 2023; Pai et al., 2013]. Map of U. P. with colored codes representing population densities on districts in India is shown in Figure 1. In the present study, data of 65 of 75 districts of UP were considered since the available data of remaining districts was not accessible.

U. P. is a critical region for studying heat waves due to its vast population, climatic diversity, and high vulnerability [India Meteorological Department (IMD), 2023]. Its dense rural population, rapid urbanization and lower access to health care and cooling system

in comparison to other IGP states and its key roles in India's agriculture system make it important to study the HW and its impacts (Goyal et al., 2023; Pandey et al., 2024; World Bank, 2022).

2.2 Extraction of data from PRECIS

In this research a PRECIS Version 2.0 was utilized, and the horizontal resolution of simulation was 25 km x 25 km. The data collection was done on PRECIS Version 2.0 model because this model

has demonstrated high potential of producing high resolution regional climate projections that are precisely specific to the impact assessment research in South Asia. PRECIS is a downscaling method developed by the Hadley Centre, UK Met Office, to dynamically downscale the outputs of Global Climate Models (GCM) to a smaller spatial resolution (typically 25–50 km), which is better suited to represent local climatic variability over heterogeneous surfaces like U. P., where monsoon processes and land surface heterogeneity have a strong role in controlling extreme values of temperature. The fact that it is easy to configure, has been successfully validated in a number of Indian studies (Rao et al., 2014; Rajbhandari et al., 2015). The data of temperature and humidity are extracted in the analysis purpose using A1B emission scenario in PRECIS model. This scenario (AIB) of emission is commonly applied in simulations of PRECIS model in India because it shows a balanced and moderate trend of future GHG emissions. A1B scenario presupposes the rapid economic development, increase of the level of technology and the balanced utilization of fossil and non-fossil energy sources, which is why this scenario is appropriate in developing countries such as India. It offers a medium-term warming outlook of about 2–3 degree Celsius by the closing of the 21st century that can be applied in evaluating temperature changes and heatwave potentials in Indian metropolitan areas (Kumar et al., 2011). Also, the A1B scenario is the default driving of PRECIS model of the Hadley Centre, which ensure consistency and comparability with previous Indian climate studies (Jones et al., 2004). Its application support in the production of reliable regional forecasts of temperature that are consistent with global modeling.

The PRECIS Regional Climate Model (RCM) has been applied in this research and is based on the hybrid vertical coordinate system with 19 levels and operates as an atmospheric land surface limited area model (Wilson et al., 2011). The main variables to be taken into account as the lateral boundary forcings are the atmospheric pressure, horizontal wind elements and humidity which are derived in HAD-GEM2-ES-GCM (Wilson et al., 2011). There was a day-by-day extraction of the data using NATCOM data extraction tool that follows the direction of the extraction tool manual provided in IITM, Pune (Dhiman et al., 2011).

The paper is based on the daily data, which were further extrapolated to determine the results in the fortnightly, monthly, quarterly, half-yearly, and yearly results. The statistics of the monthly mean meteorological parameters such as relative humidity, maximum temperature, and minimum temperature of various districts of the State of U. P. have been taken over three separate periods covering 30 years each. The 30-year period was then chosen as the definition of the base climatology in compliance with WMO recommendation which states that a 30-year interval is the most common period used to compute climate normals to represent the average state of the climate and the use of a 30-year period will minimize the influence of interannual variability (World Meteorological Organization (WMO), 2017). The time slices 1961–1990, 2021–2050, and 2071–2098 are widely used in PRECIS simulations to represent baseline, mid-century, and end-century climate conditions. The period of 1961–1990 is a commonly used as global climatological reference in both the IPCC assessments and the regional climate studies following the WMO and the period was chosen as the baseline [Jones et al., 2004; World Meteorological Organization (WMO), 2017]. The near-term to mid-term future is the 2021–2050 period, which corresponds to the timeframe of adaptation and policy planning when the role of natural

variability as well as anthropogenic effects are dominant. The end of the century projection (2071–2098) is the long-term equilibrium reaction of the climate system when it is forced into sustained GHG emission over the long term. These time slices can be seen as the coincidence of the experimental design of PRECIS created by the Hadley Centre, which is generally a simulation of climate between 1950 and 2099 with SRES or RCP scenarios (Jones et al., 2004).

2.3 Determination of heat wave (HW) and heat index (HI)

The definition of a heat wave can vary depending on geographical, climatic, and socio-economic contexts. Hence, it is not wrong to state that HW definition are not fixed, standard and Global definition and quoted by the author in several manuscripts (Awasthi et al., 2022b). However, WMO in general defined HW as a prolonged period of excessively hot weather that may be accompanied by high humidity, typically lasting at least two consecutive days with temperatures significantly higher than the average maximum of a particular region [World Meteorological Organization (WMO), 2017]. In some regions, heat waves can last for several weeks or even months, while in other areas, they may occur for only a single day with very high temperatures (De Polt et al., 2023; Schielicke and Pfahl, 2022). In certain cases, a heat wave might not even be officially recognized because what feels extremely hot in one region may be considered normal in another, depending on local climate and people's usual temperature experiences Similarly, IMD's HW criteria also vary with geography, considering that plains (maximum temperature reaches 40 °C or more) and hilly (30 °C or more) regions experience heat differently. While plains require higher temperature thresholds to be considered as HW, while hilly areas have lower thresholds since they are normally cooler. In the present paper, HW is defined as the condition in which the maximum temperature at any place continues to be above 45 °C for two consecutive days.

Temperature alone cannot show how hot it actually feels. Therefore, the HI is used by considering the humidity which gives a clearer picture of real heat stress on people. HI combines temperature and humidity to show the actual level of heat stress on the human body. The Heat Index (HI) represents the "apparent temperature," or how hot it feels to humans by combining the effects of air temperature (T) and Relative Humidity (RH). The concept originated from the work of Steadman (1979), who developed a detailed physiological model linking environmental conditions to human thermal comfort. Steadman's model accounted for parameters such as vapor pressure, clothing insulation, and metabolic rate, leading to a complex computation of perceived temperature. To make this concept operationally practical for weather forecasting, the U. S. National Weather Service (NWS) simplified Steadman's results through empirical regression. Rothfusz (1990) fitted a multiple polynomial regression to Steadman's computed apparent temperatures, producing the widely used formula: ("Heat Index, Apparent Temperature").

$$HI = -42.379 + 2.04901523 * T + 10.14333127$$
$$* RH - 0.22475541 * T * RH - 0.00683783 * T2$$
$$- 0.05481717 * RH2 + 0.00122874 * T2 * RH$$
$$+ 0.00085282 * T * RH2 - 0.00000199 * (T * RH)$$
$$2 \ for \ T \geq 80^{\circ} F \ or \ RH \geq 40\% HI = -42.379 + 2.04901523$$

TABLE 1 Heat index chart (National Oceanic and Atmospheric Administration, NOAA).

Heat index	Possible heat disorders for people in higher risk groups	Category
130 °F or higher (55 °C or higher)	Heatstroke/sunstroke highly likely with continued exposure	Extreme danger
105 °F to 130 °F (41 °C to 55 °C)	Sunstroke, heat cramps or heat exhaustion likely, with heatstroke possible with prolonged exposure and/or physical activity	Danger
90 °F to 105 °F (32 °C to 41 °C)	Sunstroke, heat cramps and heat exhaustion possible with prolonged exposure and/or physical activity	Extreme caution
80 °F to 90 °F (27 °C to 32 °C)	Fatigue possible with prolonged exposure and/or physical activity	Caution

HI alert according to NOAA's National Weather Service (National Weather Service Heat Safety)[1] is used in the present study and shown in Table 1. The table categorizes the potential health impacts of varying HI levels on people, particularly those in higher risk groups. Risk of sunstroke and heatstroke is extremely high when HI value is 130 °F (55 °C) or higher and classify as "Extreme Danger." When the HI lies between 105 °F to 130 °F (41 °C to 55 °C), prolonged exposure result in high chance of sunstroke, heat cramps, or heat exhaustion, classify as "Danger." For a HI in the range of 90 °F to 105 °F (32 °C to 41 °C), the chances of sunstroke, heat cramps, and heat exhaustion increases with prolonged exposure, thus expecting "Extreme caution." If the HI values are in the range of 80 °F to 90 °F (27 °C to 32 °C), symptom of fatigue is possible with extended exposure or physical activity, marked under "Caution." This classification system utilities in identifying the severity of heat-related health concerns and informs appropriate mitigation measures.

2.4 Data processing and generations of maps in GIS format

Daily values extracted from the PRECIS model were first organized and tabulated in Excel for further processing. Excel was used to identify and count heatwave events based on IMD criteria. Excel was also used to calculate the HI using the standard formula, and these values were grouped into different heat-stress categories for clearer interpretation. After completing the preprocessing and analysis in Excel, the datasets were imported into QGIS to prepare spatial maps (QGIS Development Team, 2024). QGIS was used to visualize the district-wise distribution of heatwaves and HI, allowing clear observation of spatial variations and temporal patterns across Uttar Pradesh.

In our study, the future HW projections were not generated through statistical extrapolation; instead, future-period HW values (2021–2050 and 2071–2098) were directly extracted from the PRECIS regional climate model outputs. HW projections were generated using daily maximum temperature outputs from the PRECIS regional climate model for the baseline (1961–1990), and future mid-century (2021–2050) and future end-century (2071–2098) periods. District-level daily temperature data were extracted,

and IMD HW thresholds were applied to identify HW events occurring for ≥2 consecutive days. The number of HW events was then counted monthly and aggregated over each 30-year period to obtain district-level HW frequencies. For stepwise details of methodology for plotting the HW and HI map, please see the Figure 2. District boundaries were overlaid to support easy comparison between regions and to highlight hotspots where heat extremes are more frequent or intense. The combined use of Excel for data handling and QGIS for geospatial mapping provides detailed spatial insights that help understand local heat conditions and support planning for heat-risk management and adaptive strategies.

3 Results

3.1 Temperature trend

By using the NATCOM data extraction tool of PRECIS model, T_{max} of 65 districts of UP is extracted by using A1B scenario and on the basis of yearly average value of all districts, values of T_{max} and T_{min} in U. P. during the three periods, i.e., base (1961–1990), middle (2021–2050) and future (2071–2098) are shown in Table 2. Table 2 displays the yearly average value of maximum temperature known as T_{max} and the minimum temperature known as T_{min} for U. P. within the stipulated periods. These values help to understand a clearer picture of past and present temperature conditions in the state and also support future temperature projections. This understanding is essential for recognizing long-term climate shifts and developing strategies to reduce the risks associated with rising heat levels in the coming years.

Average value of T_{max} and T_{min} during three studied period (Table 2) are based on the yearly average value. It is observed that minimum, maximum and mean values of T_{max} and T_{min} are increasing during the consecutive period, i.e., highest value in 2071–2098 following 2021–2050 and 1961–1990 (Table 2). Results show that mean value of T_{max} during 2071–2098 (35 °C) is more than the mean value of T_{max} during the 1961–1990 (33 °C) and 2021–2050 (34 °C), respectively. Based on the standard deviation, smallest values of T_{max} during 2071–2098 (~34 °C) is greater than highest value observed during 1961–1990 and 2021–2050 (~31 °C) and (34 °C), respectively, same result is for the T_{min} except the difference in numerical value. These observations show a significant increase in both T_{max} and T_{min} values, and this means that the average future temperatures are expected to be higher than the existing current year's maximum temperatures.
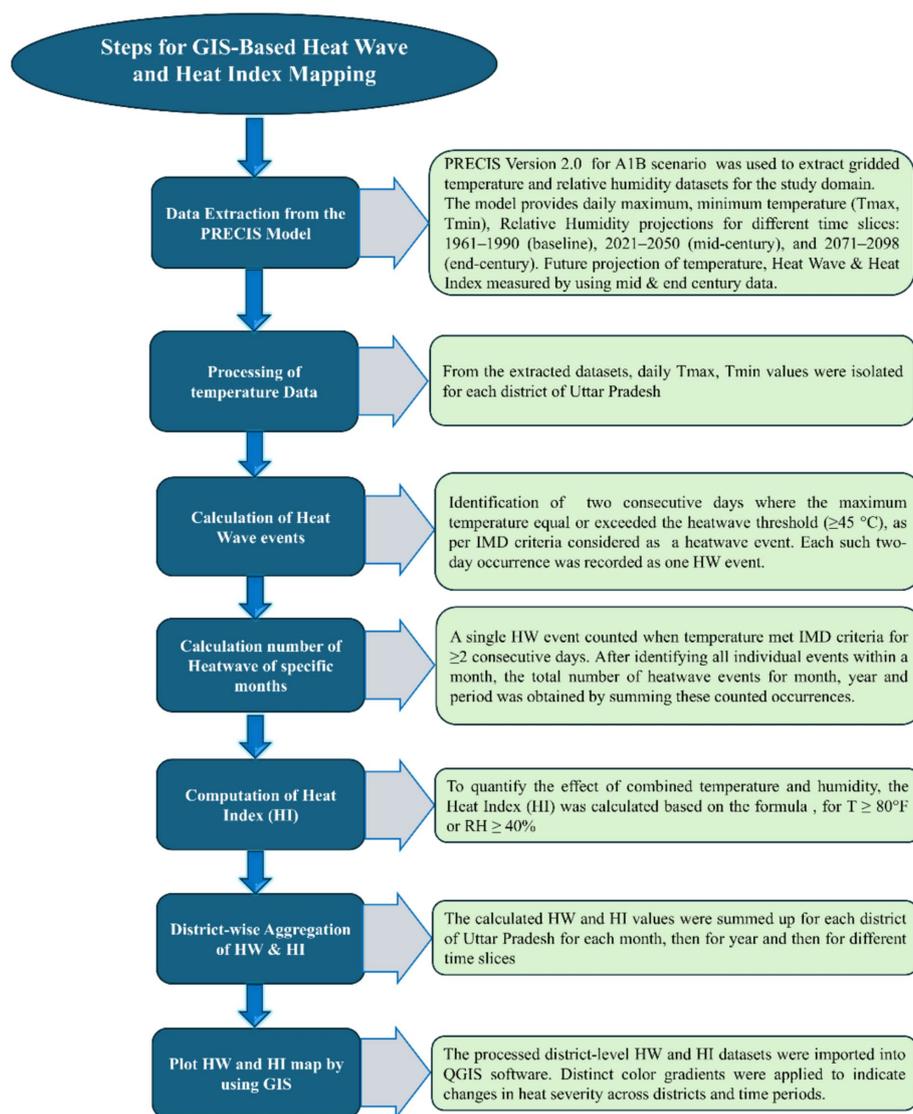
FIGURE 2
Steps for GIS-based heat wave and heat index mapping.

TABLE 2 Estimation of temperature during the periods 1960–1998, 2021–2050, and 2071–2098.

Periods	T_{max} (°C)	T_{min} (°C)
1961–1990	30 ± 0.85	19 ± 0.47
2021–2050	32 ± 0.96	21 ± 0.74
2071–2098	35 ± 1.06	24 ± 0.71

To understand the overall pattern of temperature variations across the three study periods, the maximum and minimum temperatures were compared with the long-term average for each period. This comparison, supported by the derived variables, helps reveal how temperature behavior has shifted over time. These plots are shown in the Figures 3, 4. The increase in the value of T_{max} which depicts considerable positivity for the periods including 1961–1990, 2021–2050, and 2071–2098 and higher temperature regime indicates steady rise in temperature consistently (Figure 2). Looking at the trends that are depicted in Figure 3, it was noticed that there was a relative increase in the average values of T_{max} utmost by about 0.5 °C per decade (i.e., 10 years) for the period of 2021–2050. Projected data of T_{min} in Figure 4 indicates that along with T_{max}, T_{min} is also shows overall increase in coming periods of 2021–2050 and 2071–2098, respectively, with maximum increase of about 0.5 °C per decade is observed during the period of 2021–2050.

On the whole, the results indicate that climate change has a significant impact on temperature patterns, and an increase in temperatures has produced a variety of issues. Such increase in temperatures results in various problems and causes severe threats to
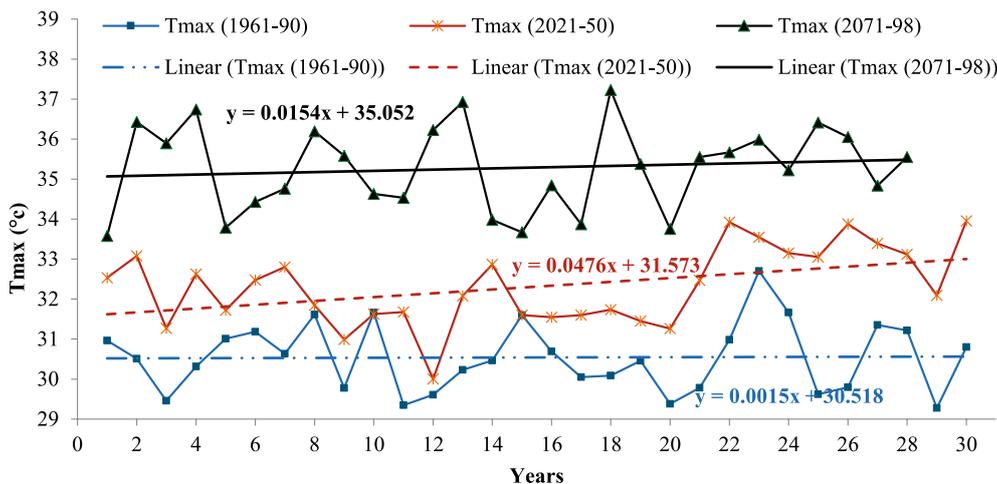
FIGURE 3
Yearly average variation of maximum temperature (Tmax) for Uttar Pradesh across the periods 1961–1990, 2021–2050, and 2071–2098.
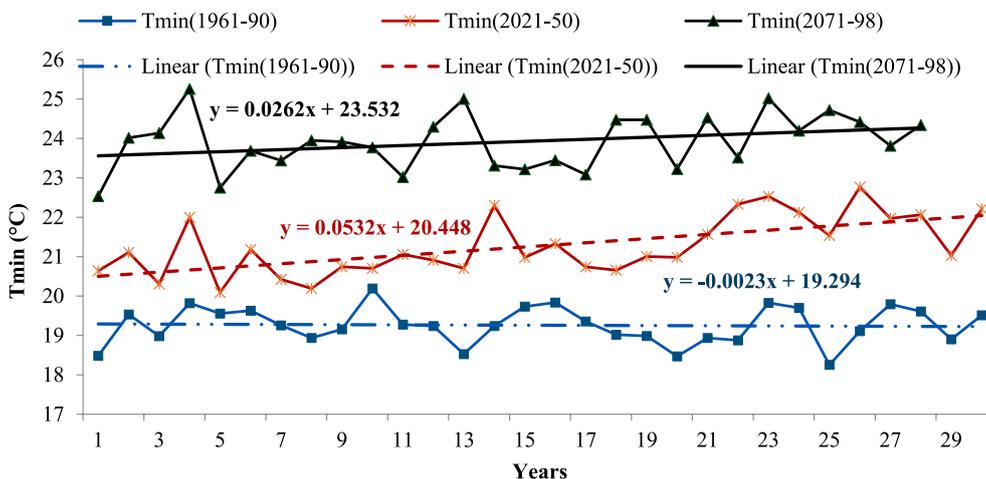

FIGURE 4
Yearly average variation of minimum temperature (Tmin) for Uttar Pradesh across the periods 1961–1990, 2021–2050, and 2071–2098.
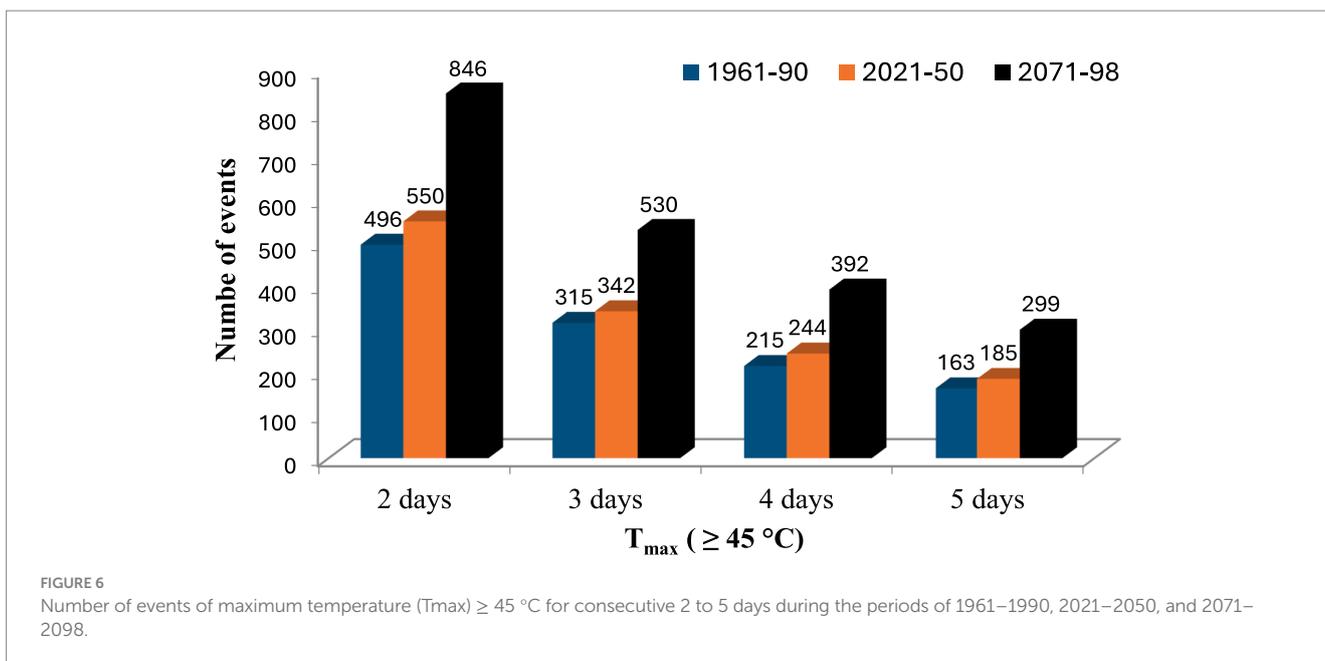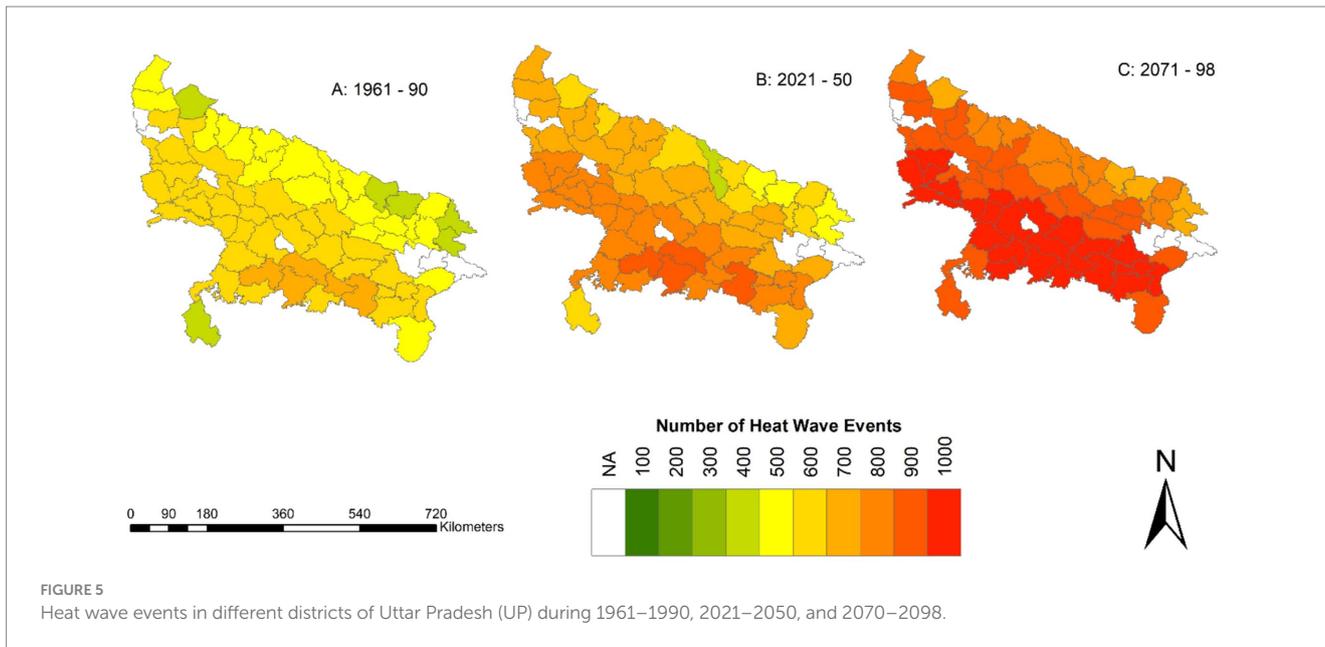
human health, especially those of vulnerable populations including children, elderly people, and individuals with underlying diseases (Yadav et al., 2023). Glacier melting also rises faster with the rise in temperatures and may lead to the loss of glaciers and the probability of landslides in mountainous areas (Awasthi et al., 2022a). In the coastal regions, any alteration in the sea level will compel people to migrate and this is the reason why there is great necessity of identifying efficient strategies to curb climate change and ensure that people adjust to the changing environmental status.

3.2 Heat wave

The occurrence of HWs is determined by considering consecutive 2 days with maximum temperatures exceeding 45 °C. Figure 5 represents the variation in the number of HW events across different districts of UP throughout the selected periods. A noticeable trend is observed, indicating an increase in the frequency of HWs over time.

Mathematical analysis reveals a significant increase in HW events during the middle and future periods, respectively, compared to the base period of 1961–1990. The southern regions of U. P., particularly Allahabad, Kaushikbhai, and Banda, experienced the highest number of HW events across all three periods, highlighting the impact of climate change on the increasing incidence of HW. To assess the intensity of HWs, the number of consecutive HW days ranging from 2 to 5 days is calculated for each period and shown in Figure 6.

Figure 6 represents the occurrence of days with Tmax ≥ 45 °C consecutive for 2, 3, 4, and 5 days for the three studied periods. The hottest days (above 45 °C), as well as numbers of the days exceeding the temperature of 45 °C are observed to be increase in coming period and maximum values are observed in 2071–2098, which indicate that both the frequency and intensity of the heat waves increase with time. Several research has revealed that when there is higher exposer to extreme weather conditions, the health risks of the people are affected in several ways due to heat related illness like heat stroke, heat exhaustion, etc. (Ebi et al., 2021; Heidari et al., 2020; McMichael, 2023;

FIGURE 5
Heat wave events in different districts of Uttar Pradesh (UP) during 1961–1990, 2021–2050, and 2070–2098.

FIGURE 6
Number of events of maximum temperature (Tmax) ≥ 45 °C for consecutive 2 to 5 days during the periods of 1961–1990, 2021–2050, and 2071–2098.

Ngwenya et al., 2018). Further, the increased temperatures and longer summer days put one at a risk of aggravating one's health conditions due to heat stress and dehydration (Kumar et al., 2022).

There is a clear increase in the duration and intensity of heatwaves, which makes it important to take timely action to reduce heat-related risks. Key measures include giving early heatwave warnings, educating people about heat risks, sharing heat advisories, improving access to cooling, and designing cities in ways that reduce the heat-island effect. These actions can prevent serious problems, increase preparedness, and protect people especially children, older adults, outdoor workers, and others who are more sensitive to extreme heat. By strengthening these measures, communities can reduce the harmful effects of rising heatwave events.

3.3 Heat index

Temperature data extracted from PRECIS Model indicate that HW events are prevalent in the months of April, May and June more than the other months. For determining the comfort level of people, the calculation has made to measure the HI to examine the combine effect of temperature and RH on the people of different districts of U. P. Analyzing the results of HI for the studied period, it can be observed that the average HI in U. P. in terms of months does not exceed 50 °C. Hence, based on the overall average value of HI (<50 °C) of all the districts for U. P. and with reference to HI chart (Table 1), people in U. P. do not undergo through the extreme danger zones in as far as heat stress is concerned.
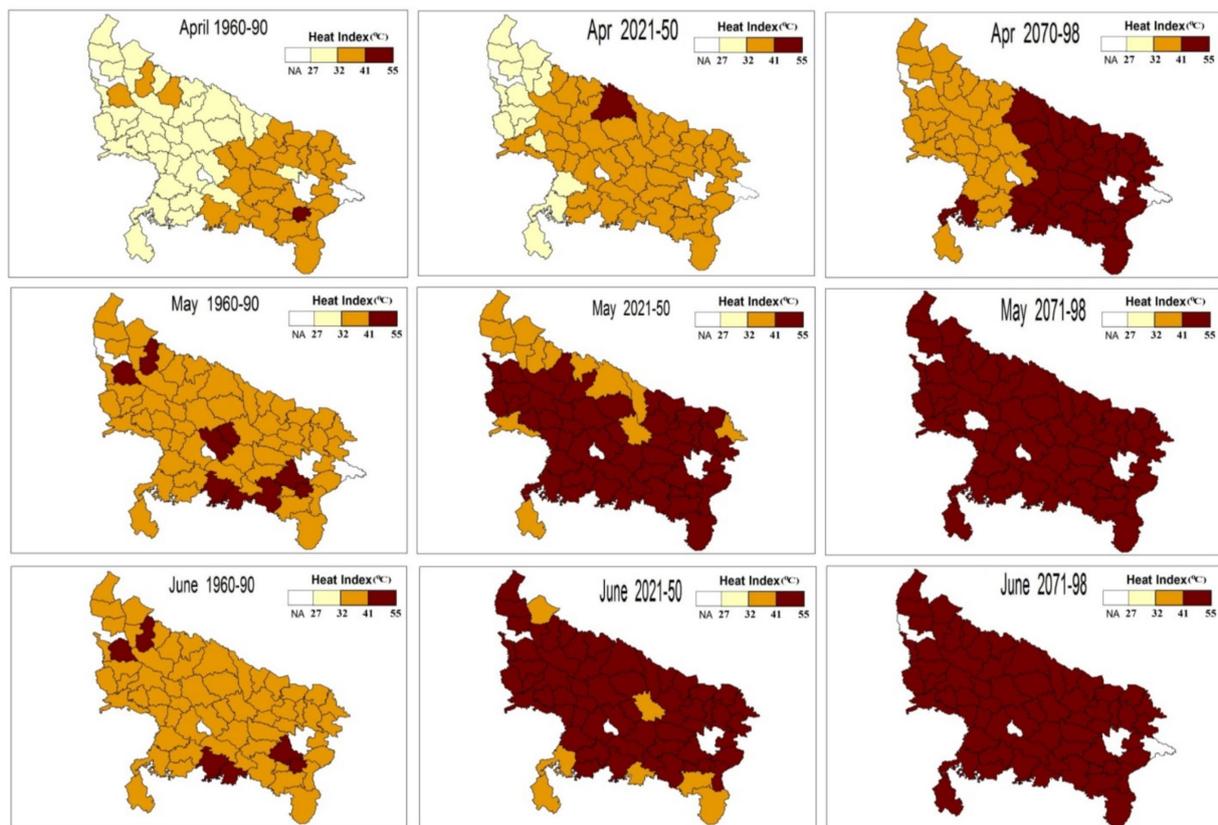
FIGURE 7
HI of different districts in UP during April, May, and June for the periods 1960−1990, 2021−2050, and 2071−2098.

Figure 7 illustrates HI of different districts of U. P. during April, May, and June of the periods 1960–1990, 2021–2050, and 2071–2098, with maximum HI values typically observed in June. In the future, HI values in various districts are projected to surpass the danger threshold (>41 °C), posing serious health risks such as sunstroke, heat cramps, exhaustion, and heatstroke, particularly during physical exertion or prolonged exposure to sunlight. During 2021–2050 and 2070–2098, nearly all districts are expected to fall within the danger zone. Gazipur, Jaunpur, Varanasi, and Chandauli emerge as the most vulnerable districts of U. P. based on the average HI values for April to June, with maximum HI reaching 48 °C. HI values are anticipated to increase by 3 and 12% during the middle and future periods, respectively, compared to the base values. Consequently, the high temperatures prevailing in these regions have detrimental effects on the population, occasionally resulting in fatalities. McMichael (2023) extensively studied the adverse effects of high temperatures in Australia, reporting over 1,000 deaths annually among the elderly population, with projections indicating a significant increase in heat wave intensity and frequency by 2050, particularly in temperate regions. Elevated temperatures are also associated with higher levels of aeroallergens and pollens, exacerbating health issues such as asthma, leading to a surge in casualties. Thus, it is imperative to implement strategies to mitigate the impacts of high-temperature events and minimize their adverse effects on public health.

4 Discussion

The spatial patterns of HWs and HI observed in this study indicate that several districts in Uttar Pradesh face frequent and prolonged periods of dangerous heat. These findings help explain why heat stress can significantly influence public health, particularly through increased heat-related illnesses, added risk for elderly populations, and additional strain on healthcare systems (Chersich et al., 2023; Sinha et al., 2022).

The results also highlight how rising heat levels may affect agricultural productivity, as extreme temperatures can reduce crop yields, disrupt growing seasons, and increase irrigation demands effects that have been widely reported in heat-sensitive regions across India (Lobell et al., 2012; Auffhammer et al., 2012). Similarly, recurring HWs intensify pressure on infrastructure and energy systems, leading to increased electricity demand, reduced cooling efficiency, and greater stress on urban environments (Santamouris, 2016). These insights provide valuable evidence for policy makers, planners, and public health agencies to develop targeted heat-action plans, district-level adaptation strategies, and climate-resilient agricultural and infrastructure responses. The observed trends also carry global significance, contributing to broader discussions on climate resilience, food security, and international public health preparedness (Intergovernmental Panel on Climate Change (IPCC), 2021).

As observed in the past research, heat waves have had great effects in Uttar Pradesh and some of the effects include pressure on agricultural crops, health crises, and rise in energy demand. Increasing temperatures and extended heat waves have changed the cropping pattern, shortened the period of crop growth, and decreased the yield of wheat by a fact of 32–34% in the heat-stressed areas (Imdad et al., 2024). An extreme heat event in 14–16 June 2023 in Ballia district is estimated to be at least twice as probable because of human-made climate change and underscores higher vulnerability to heat in the region (Climate Central, 2023). The state confirmed dozens of heat-related deaths and heat stresses in many cases, especially in outdoor workers and the elderly, during major episodes of heatwave, including the 2019 and 2023 ones (Climate Central, 2023; Vicedo-Cabrera et al., 2021). It has been demonstrated that higher temperatures significantly increase cardiovascular and respiratory risks and increases the occurrence of dehydration and heatstroke. In the 2022 heatwave, almost 36 percent of surveyed agricultural households in U. P. experienced the effects of heat waves on livelihood (Bal et al., 2022; Sphere India, 2022). Furthermore, the heat waves can cause spiked rise in electricity demand above the seasonal averages of electricity to cool the air and irrigate farms resulting in power shortages (Mideksa and Kallbekken, 2010). These effects demonstrate why Uttar Pradesh is particularly vulnerable when extreme heat is in contact with the large population and inadequate infrastructure. This makes it significant to examine heat exposure on the district level in order to understand the risks and create effective measures (Shahfahad et al., 2024a). Therefore, in this study attempts have been made where extreme temperature has been checked as well as HI of the various districts within U. P.

4.1 Significance of the research

The study provides a comprehensive analysis of HW patterns, impacts, and potential future scenarios in one of India's most populous states. This study no doubt seemed like regional study, but the study of HWs in U. P., India, have global significance for a number of reasons. First, localized research like this one provides vital data for improving global climate models. These models are critical for projecting future climatic scenarios and planning effective climate change adaptation strategies that benefit areas throughout the world (Liyanage et al., 2024). Furthermore, knowing the patterns and implications of HWs in U. P. gives crucial visions that may be used to improve global adaptation strategies, allowing other regions to prepare and build strength against the similar climate pattern (Calovi et al., 2022). Public health is another important aspect of this study, which has worldwide consequences. HWs pose important worldwide health concerns (Ndlovu and Chungag, 2024), and data from U. P. contribute to a better understanding of heat-related health effects. This knowledge is critical for influencing worldwide health standards and policies focused at minimizing these hazards, which will improve global health responses (Bolan et al., 2023). Additionally, the epidemiological knowledge gained from this research may help to monitor and predict the health consequences of HWs, boosting the preparedness of the worldwide medical infrastructure (Szagri et al., 2023).

The impact of HWs on U. P. agriculture has extensive worldwide implications. As one of the key agricultural regions, crop output interruptions caused by HW can have significant impact on food supply chains, adjusting pricing and availability worldwide (Tchonkouang et al., 2024). To manage the food security globally, recognizing of these implications is very important (Tchonkouang et al., 2024). Furthermore, the study might recognize sustainable farming practises that mitigate the outcomes of HW (Foguesatto et al., 2020) and may be used in other agricultural localities facing similar climatic changes throughout the world.

Finding of this study's are useful and play an important role to design policies and agreements worldwide to target for lowering of GHG and mitigating climate change (Tang, 2019). Policymakers may utilize the information to create targeted actions, ensuring that initiatives are based on real-world impacts (Son et al., 2024; Xu et al., 2023). Furthermore, explaining the consequences of HWs in U. P. might contribute to attract international global funding and assistance for climate mitigation initiatives. Finally, the study is critical to global economic stability (Yin et al., 2022). The work contributes to the development of worldwide solutions for mitigating the economic implications of HWs, such as lower labor productivity and infrastructure stress (Cheng et al., 2021). This is crucial for maintaining economic stability and fulfilled different sustainable development goals in the context of climate change (Zhang et al., 2019). This research contributes to several Sustainable Development Goals (SDGs), SDG 3 (Good Health and Well-Being) by focusing on addressing health hazards related to heat exposure, SDG 11 (Sustainable Cities and Communities) by focusing on urban resilience to extreme heat, and SDG 13 (Climate Action) by responding to climate projection and climate adaptation analysis (Pandey et al., 2025). It also has an indirect effect on SDG 6 (Clean Water and Sanitation) and SDG 7 (Affordable and Clean Energy) because increasing temperatures impact the availability of water and the amount of energy required to cool the system (Choudhury and Awasthi, 2025).

The research is important due to the fact that it gives the district-level analysis of HW and heat HI in U. P. and it provides a better perspective on the variation of extreme heat in the state. Determining when and where the high-intensity heat events take place, the research would help to point out the most exposed districts and emphasize the trends that were not studied before. The results can be applied in enhancing early-warning systems, district-level heat action plans, and resource allocation priorities in areas experiencing greater heat stress by local authorities and policymakers. The research also contributes to the preparedness of the community health by demonstrating the potential of aggravating the thermal discomfort and health risks by high HW and HI conditions. Overall, the study is directed on the scientific basis of the heat-related risk management and climate adaptation in U. P. By generating district-level evidence on heatwave and heat-index patterns, the study not only supports local decision-making but also contributes to the global understanding of how densely populated, climate-sensitive regions can prepare for rising thermal extremes.

5 Limitations

While the PRECIS model is used to generate climate forecasts for India, using it for HW studies in UP comes with certain limitations. One of the important limitations is its coarse spatial resolution (25–50 km) which is unable to consider the microclimatic variations

across the state. Uttar Pradesh's diverse geographic features include the northern foothills of the Himalayas, the Gangetic plains, and heavily populated urban areas like Lucknow and Kanpur. The diversity leads to specific localized heatwave phenomena, including pronounced urban heat islands, which are smoothed over by PRECIS model, leading to potential under or overestimation of HW intensity at finer scales.

Another major issue is the biases in temperature extremes simulation. The observed frequency, duration, and severity of extreme heat events often struggle to replicate in PRECIS simulations due to over-simplified model physics and lack of resolution for sub-grid scale processes. Additionally, dependence on a single Global Climate Model (GCM), amplifies these uncertainties. Any systematic bias present in the GCM gets aggravated in PRECIS outputs, hence, narrowing the scenario range and heatwave projection confidence.

In addition, PRECIS provides a simplification regarding the representation of the processes that occur at the land surface as well as the aerosols. Important heatwave drivers, including the irrigation cooling effect in the Indo-Gangetic plains, biomass burning and industrial emissions aerosol loading, as well as rapid urbanization, are not accurately represented. It also has the limitation of static assumptions regarding the socioeconomic parameters and land use, including urban sprawl, agricultural activities, and land cover transformating sustaining in the future, which significantly affect local heatwave dynamics. Lastly, working toward validation is difficult in this case due to the lack of high-resolution observational data, particularly in the countryside, which prevents the elimination of biases and a proper evaluation of the model's accuracy in the heatwave analysis for U. P.

These gaps can be narrowed by integrating advanced bias-correction methods, using high resolution datasets like IMDAA reanalysis (Rani et al., 2021), and complementing PRECIS with next-generation models such as CORDEX regional outputs or CMIP6 Earth System Models. The use of advanced land data assimilation methods and coupled numerical weather prediction models (Lodh et al., 2024) is expected to produce more refined projections, with better representation of aerosols, land–atmosphere processes, and uncertainty ranges leading to more accurate and actionable insights on HWs in U. P.

6 Conclusion

Increasing trends of the temperature are observed in the studied period especially in the coming time period, i.e., 2021–2050 and 2071–2098 mostly in all the districts of U. P. The mean annual T_{max} and T_{min} value increased by 0.5 °C per decade during the period of 2071–2098. Number of HW events are increasing alarmingly in the coming periods, i.e., 2021–2050 and 2071–2098 with respect to the period from 1960 to 1990. Frequency and prolonged extreme temperature events, i.e., $T_{max} > 45$ °C is predicted to be maximum in the 2071–2098 period. Comfort level on the basis of HI and average value of temperature indicates that Gazipur, Jaunpur, Varanasi and Chandauli will be the most impact district of the U. P. in the coming decade especially in the period of 2071–2098. Calculated value of HI on the basis of extracted data shows 12 percent increase in 2071–2098 with respect to 1960–1990 and most of the district coming under the danger zone as per the NOAA's HI alert. Since the results show that in the coming decade, frequency and intensity of HW increases more abruptly, hence it is necessary for the government agency to plan

adaption measures to reduce the effects of heat extreme events especially on the sensitive group like children etc. There is a need to strengthen existing public health approaches to control disease and health protection, to anticipation and early detection of potential effects, and to provide information to the public and health professionals.

In summary, at the local scale, the study offers essential evidence to guide district-specific heat-risk mitigation and adaptation planning across U. P. At the global level, these findings add to the growing scientific understanding of extreme heat dynamics, supporting worldwide efforts to build climate-resilient communities in the face of escalating temperature extremes. The study is a critical component of research in addressing the issues raised by climate change since these insights are critical for worldwide efforts to mitigate and adapt to climate change.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

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