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ARTICLE

Study of the Present and Future Scenario Heatwaves and Heat Stress for the Few Important States of India

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ABSTRACT

India is highly vulnerable to climate change and is going to increase its average annual temperature over the next few decades. The impact of heatwaves and related mortality is a concern for the country. In this paper, we aim to study the heatwaves and heat stress-related Heat Index vulnerability using heat index temperature. In this analysis, a heat index temperature is calculated based on temperature and relative humidity for six different states (Delhi, West Bengal, Punjab, Uttar Pradesh, Andhra Pradesh, and Madhya Pradesh) of India to determine the heat stress vulnerability for which heat cramps and heat strokes are possible. Our analysis shows that most of the heatwaves and severe heatwaves occurred during 2010 for all the states. The heatwaves are observed only in the summer months. All the states of our study reached the Extreme Caution category of the Heat Index showing the Danger to Extreme Danger category during April to June. Future projection scenarios show an increase in heat stress-related vulnerability. SSP2-4.5 scenario showed that Delhi, Punjab, and West Bengal reached an Extreme Danger state during June for which death due to heat strokes is possible under continued exposure to heatwaves. The HI related vulnerability of SSP5-8.5 is like SSP2-4.5 except for Andhra Pradesh which shows an Extreme Danger state in May and June during which heat strokes are possible under continued exposure to heatwaves. This study provides spatial variability of heat stress and Heat Index vulnerability which may help adopt future strategies for heat-related policy implication.

Keywords: Heatwaves; Heat Index Temperature; Mortality; Relative Humidity

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1. Introduction

Heatwaves and heat stress are increasingly becoming significant concerns for the environment and public health in the age of global climate change [1–7]. The global mean temperature has warmed by 0.89°C in this century due to anthropogenic activity and the increase in annual mean temperature for India is 0.85°C [8,9]. The frequency, intensity, and duration of heatwaves have been rising worldwide and are expected to increase by 30 times compared to the present climate by the end of the 21st century [10–13], which will have detrimental effect on agriculture, infrastructure, economy, and human health [14–18]. The effect of temperature on mortality rates varies with location and population [19]. India has experienced multiple heatwaves that have intensified in frequency over the past decades [20]. Particularly, northern India has shown many heatwaves [21]. Frequent and intense heatwaves occurred across north-western India, encompassing Rajasthan, Punjab, Haryana, and Madhya Pradesh. Das et al. and Kumar et al. analysed the fact that the number of heatwave events in Delhi is higher than in Kolkata [22,23]. Research indicates that by 2100, the heatwave frequency, severity, and duration will increase across different world regions, including the Indian region [24,25]. Heatwaves are expected to have an increasing impact on death rates and severe illnesses among older and urban poor people [21,26–28]. They affect thermal comfort and are linked with a rise in the mortality rate and potential disruptions to infrastructure [29–31]. Heatwave-induced mortality has increased by 62.2% in the last 20 years with a 60% rise in the fatality rate attributed to heatwaves in Andhra Pradesh [32]. Heat exposure can result in heat stroke and hyperthermia [33]. Naskar et al. (2024) found that a significant increase in both temperature and humidity will increase the likelihood of accidents and fatalities brought on by heat stress conditions [34]. Heatstroke fatalities in India were predominantly recorded in larger states, including Uttar Pradesh, West Bengal, and Andhra Pradesh [35].

The feel-like temperature is referred to scientifically as the Heat Index (HI), which considers both actual temperature and humidity [36,37]. HI is a key index for environmental health research related to thermal comfort [38]. It can be considered a biometeorological index linked to the thermal perception of humans informing on their well-being conditions and about the risk to human health due to extreme temperature events, which is why it has been applied in the investigation of adverse health impacts due to heat stress [39–42]. Human exposure to high temperatures and relative humidity can lead to heat stress, heat stroke, and dehydration. People living in urban environments may be at greater risk than those living in rural areas due to higher heat indexes due to a combination of humidity and temperature [43–48]. Mohan et al. (2013) conducted a study using the HI to assess thermal comfort conditions across five metropolitan cities in India [49]. Various indices exist in the literature for assessing heat stress. For instance, Dash et al. (2017) used various heat indices and stated that they varied from region to region [50]. They also stated that HI is very close to the Universal Thermal Climate Index (UTCI) and humidex for Delhi, Mumbai, and Chennai, whereas, for the case of Kolkata, HI values are very close to Wet-bulb Globe Temperature (WBGT). An analysis of these four metropolitan cities using UTCI revealed that great-to-severe discomfort categories were observed in Kolkata and Chennai as compared to other cities [23]. Additionally, Bernard and Iheanacho (2015) demonstrated that HI can be a useful surrogate for WBGT to screen for potential heat stress exposure [51].

Goyal et al. (2023) have determined the impact of future climate Shared Socioeconomic Pathways (SSP) scenarios, specifically SSP2-4.5 and SSP5-8.5, on the characteristics of heatwaves over the homogenous temperature zones of India and found that the coastal, Interior Peninsular and North-Central regions are expected to experience more intense and frequent heatwaves under both the scenarios [52]. The heat index is projected to rise by the end of the century under both scenarios (SSP2-4.5 and SSP5-8.5) with a more pronounced increase under the SSP5-8.5 scenario [53]. Norgate et al. (2024) highlighted that SSP5-8.5 is considered the most extreme scenario in terms of emission and may be useful for successful mitigation efforts to decrease the occurrence and duration of heatwaves experienced in India by the end of the century [54].

One of the primary motivations for studying heatwaves and heat stress is their profound impact on public health. By understanding the patterns and effects of heatwaves, we can develop effective public health interventions, early warning systems, and community outreach programs to mitigate these risks and protect the most vulnerable members of society [4,55,56]. By studying heatwaves and heat stress, we can develop heat-resistant crop varieties, improve agricultural practices, and implement strategies to protect livestock, thereby ensuring food security and the livelihoods of farmers [57,58]. The economic impact of heatwaves and heat stress is substantial. The strain on energy systems due to increased air conditioning use can result in power shortages and infrastructure damage. Understanding the economic implications of heatwaves can help businesses and governments plan and invest in resilience measures, minimising financial losses [3,23,59–61].

Therefore, the primary objective of this research is to investigate the vulnerability related to heat stress for March, April, May, and June for the **present scenario** (**2001–2024**) and to evaluate the vulnerability during **future scenarios** (**2025–2049**) using Climate Model Inter-Comparison Project: Phase 6 (CMIP6) data for the states of Punjab, Delhi, West Bengal, Uttar Pradesh, Madhya Pradesh and Andhra Pradesh, aiming to better prepare during heatwave and severe heatwave conditions.

2. Study Regions, Datasets and Methodology

2.1. Study Regions

The study regions are the six states of India: Punjab, Delhi, West Bengal, Uttar Pradesh, Madhya Pradesh, and Andhra Pradesh (**Figure 1**).

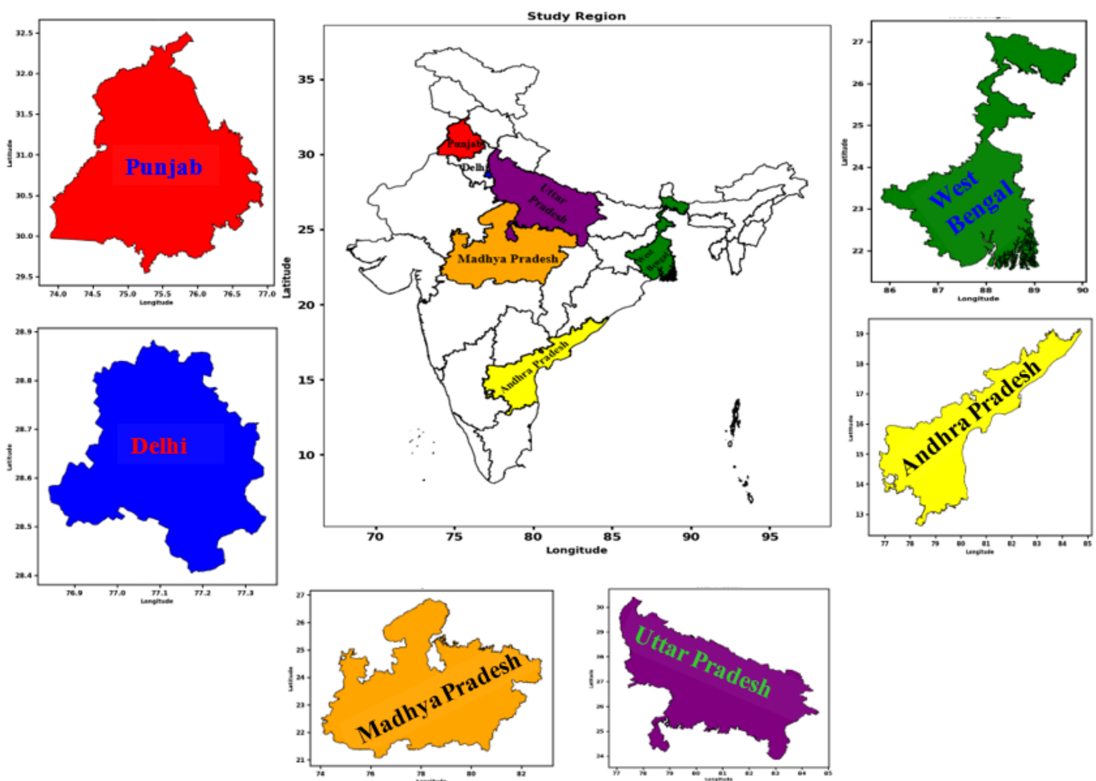

Figure 1. Geographical Locations of the Study Regions. The Enlarged Versions of the Six States of India are Shown Along with All India Maps.

2.2. Datasets

The hourly dataset for temperature and relative humidity for the present scenario (2001–2024) is taken from the fifth-generation European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA5) of the global climate having a grid resolution of 0.25° × 0.25° [62]. These data are publicly accessible through the Copernicus Climate Data Store (CDS).

The CMIP6 climate change projections for the future include four SSP scenarios that address the growing demands of the climate science community [52,63]. Based on the comparison among the different models, the Centre National de Recherches Meteorologiques: Climate Model Version 6 (CNRM-CM6-1) performs best for spatial temperature over India and is used in our study for SSP2-4.5 & SSP5-8.5 scenarios for the future period (2025–2049) [54]. These datasets are available via the Earth System Grid Federation (ESGF) portal.

2.3. Methodology

2.3.1. Calculation of Heatwaves

Heatwaves have been calculated based on the IMD criteria based on the Normal Maximum Temperature (T_{max}). Heatwaves or severe heatwaves are defined by diurnal T_{max} thresholds. The climate normal (average of 30 years) of diurnal T_{max} has been calculated using

$$\bar{x}_i = \frac{\sum_j^n x_i^j}{n} \quad (1)$$

where i = 1,2,3……365 in days, j = 1,2,3,4……30, and n = 30 [64]. The heatwaves or severe heatwaves in the plains may be classified as stated in **Table 1**, which is used in our study [23].

Table 1. Classification of Heatwaves as per IMD Criteria [23].

Normal of T_{max} is less than 40 °C	**Heatwaves:** If diurnal Tmax is 5 °C or 6 °C ≥ from Normal Tmax. **Severe heatwave**: If diurnal Tmax is 7 °C ≥ from Normal Tmax.
Normal of T_{max} is greater than 40 °C	**Heatwaves**: If diurnal Tmax is 4 °C or 5 °C ≥ from Normal of Tmax. **Severe heatwave**: If diurnal Tmax is 6 °C ≥ from Normal Tmax.

Source: IMD Criteria Document.

2.3.2. Calculation of Heat Index Temperature

HI is the measure of heat stress and is calculated based on the ambient air temperature and relative humidity. Generally, the National Weather Service (NWS) equation [65,66] is used to estimate temperature and the level of danger associated with varying relative humidity percentages. The Rothfusz equation for HI is used in this study considering the criteria of air temperature (>26°C) and humidity (>39%) as used by earlier studies over India and given by

$$\begin{aligned} HI = & -42.379 + 2.04901523T + 10.1433127R - 0.2247554TR \\ & - 6.8378\times10^{-3}T^2 - 5.481717\times10^{-4}R^2 + 1.22874\times10^{-3}T^2R \\ & + 8.5282\times10^{-4}TR^2 - 1.99\times10^{-6}T^2R^2 \end{aligned} \quad (2)$$

where T is the ambient dry air temperature (°F) and R is the relative humidity in percentage [66–68].

The heat index in terms of temperature and corresponding categories of fatality shown in **Table 2** is used in this study [53,69].

Table 2. Categories of Heat Stress-Related Problems Based on HI (see NWS Heat Index Guide).

Celsius	Categories
27–32 °C	**Caution:** fatigue is possible with prolonged exposure and activity. Continuing activity could result in heat cramps.
32–41 °C	**Extreme Caution:** heat cramps and heat exhaustion are possible. Continuing activity could result in heat stroke.
41–54 °C	**Danger:** heat cramps and heat exhaustion are likely; heat stroke is probable with continued activity.
Over 54 °C	**Extreme Danger:** heat stroke is imminent.

3. Results and Discussion

In this study, we mainly focus on the identification of Heatwaves and Heat Index Temperatures in Delhi, West Bengal, Punjab, Uttar Pradesh, Madhya Pradesh, and Andhra Pradesh. The future projection of heatwaves and heat stress based on HI is also analysed using CMIP6 model SSP2-4.5 and SSP5-8.5 scenarios. The result section is divided into two sub-sections. Identification of heatwaves based on T_{max} were carried out in Section 3.1. Analysis of HI and related heat stress categories has been carried out in Section 3.2.

3.1. Heatwaves and Its Characteristics

The present scenario heatwave has been identified for the study region using the maximum temperature (black line) along with the climatology of maximum temperature (blue line) and different categories of heatwave threshold limits (green-coloured lines as heatwaves and red-coloured lines as severe heatwaves) are shown in **Figure 2** to **Figure 6**. The prominent variability of a severe heatwave over the 90th percentile threshold has been shown in the red-shaded area. The IMD heatwaves category based on the classification of normal maximum temperature (**Table 2**) has been used here.

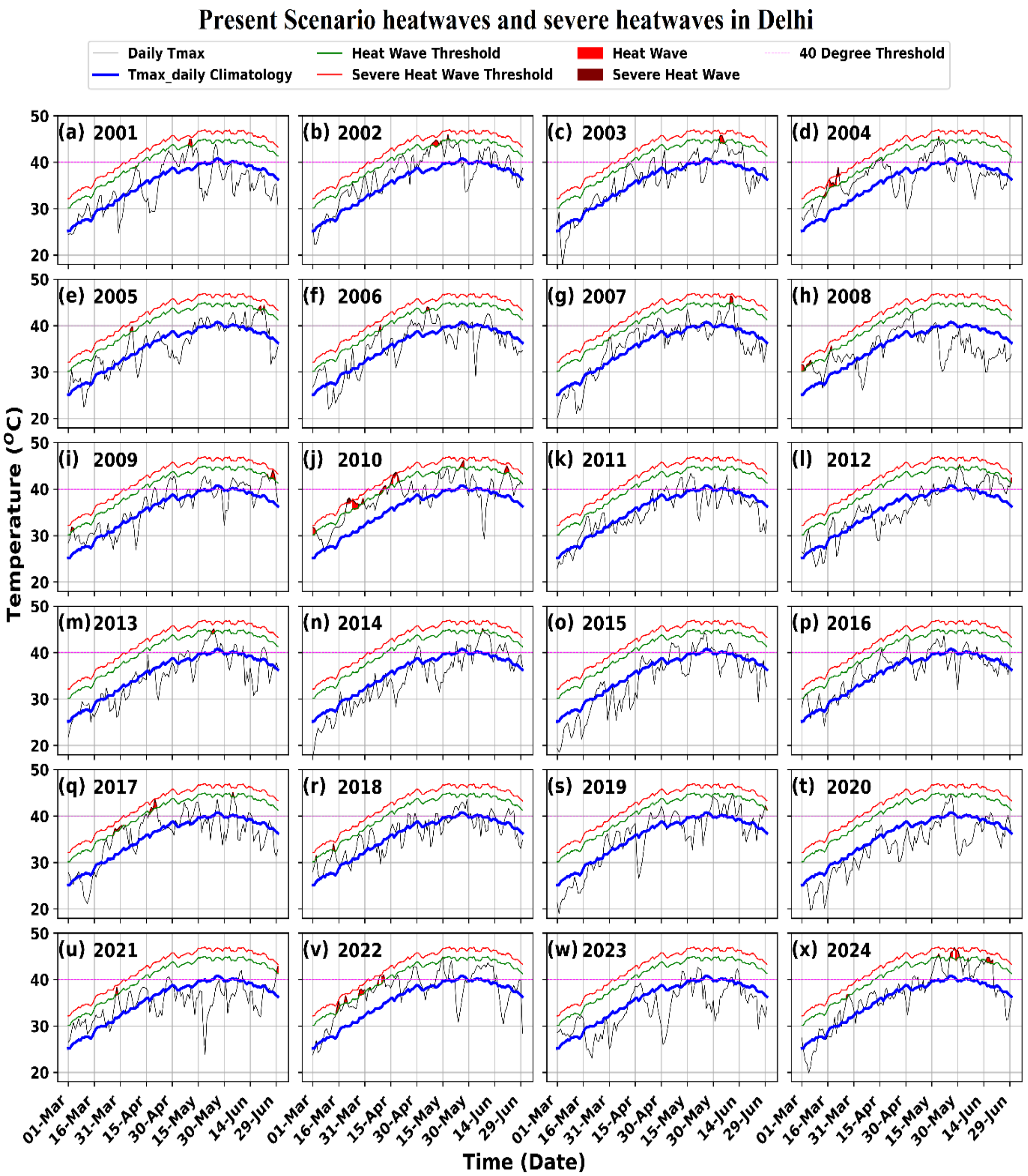

Figure 2. Yearly Variations of Heatwave (Mark Red) and Severe Heatwave (Mark Magenta) for the Present Scenario ((**a**)–(**x**): 2001–2024) for the Summer Months (March–June) for Delhi. The Meaning of the Colour Lines is Provided in the Legend at the Top.

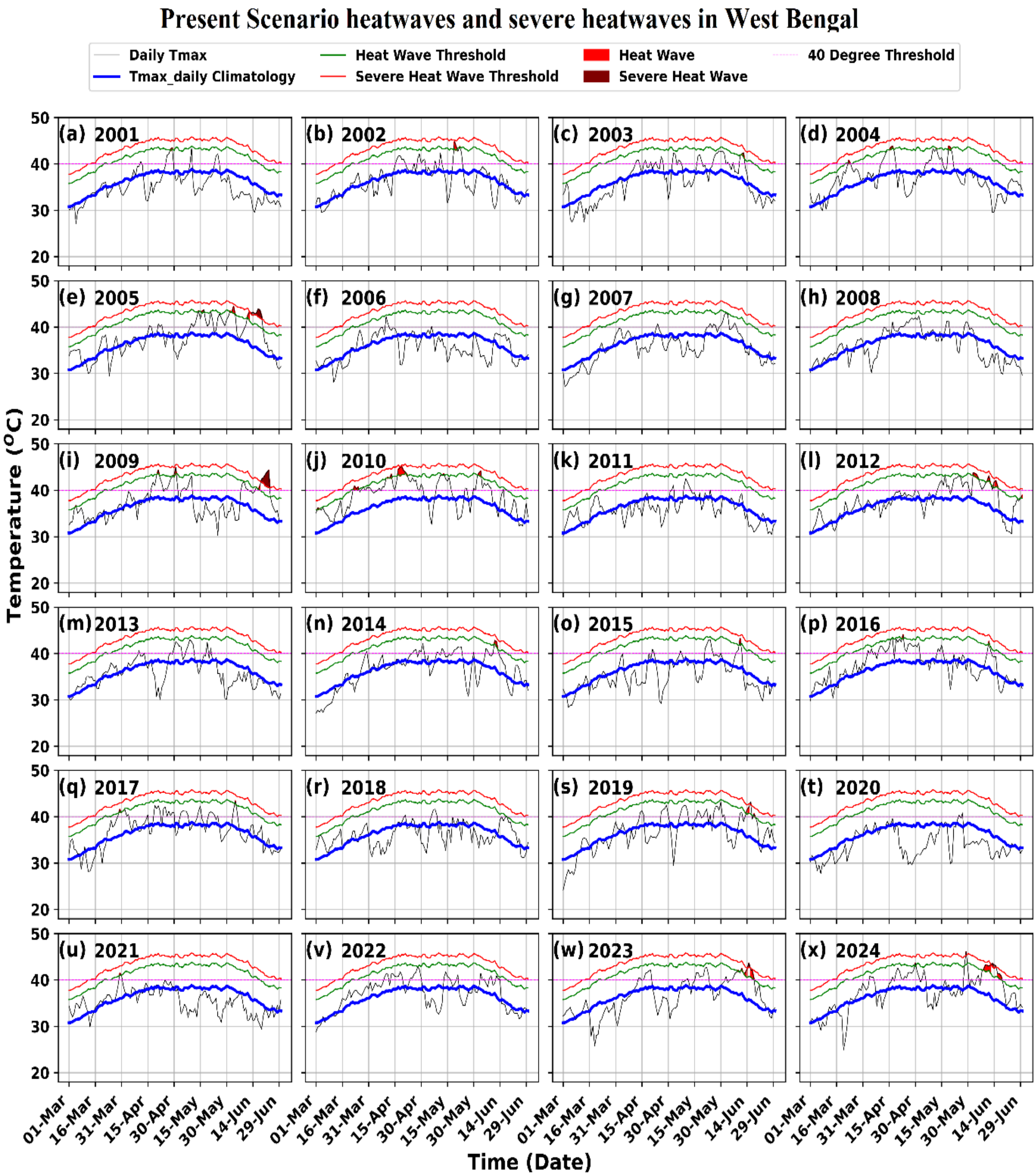

Figure 3. Yearly Variations of Heatwave (Mark Red) and Severe Heatwave (Mark Magenta) for the Present Scenario ((**a**)–(**x**): 2001–2024) for the Summer Months (March–June) for West Bengal. The Meaning of the Colour Lines is Provided in the Legend at the Top.

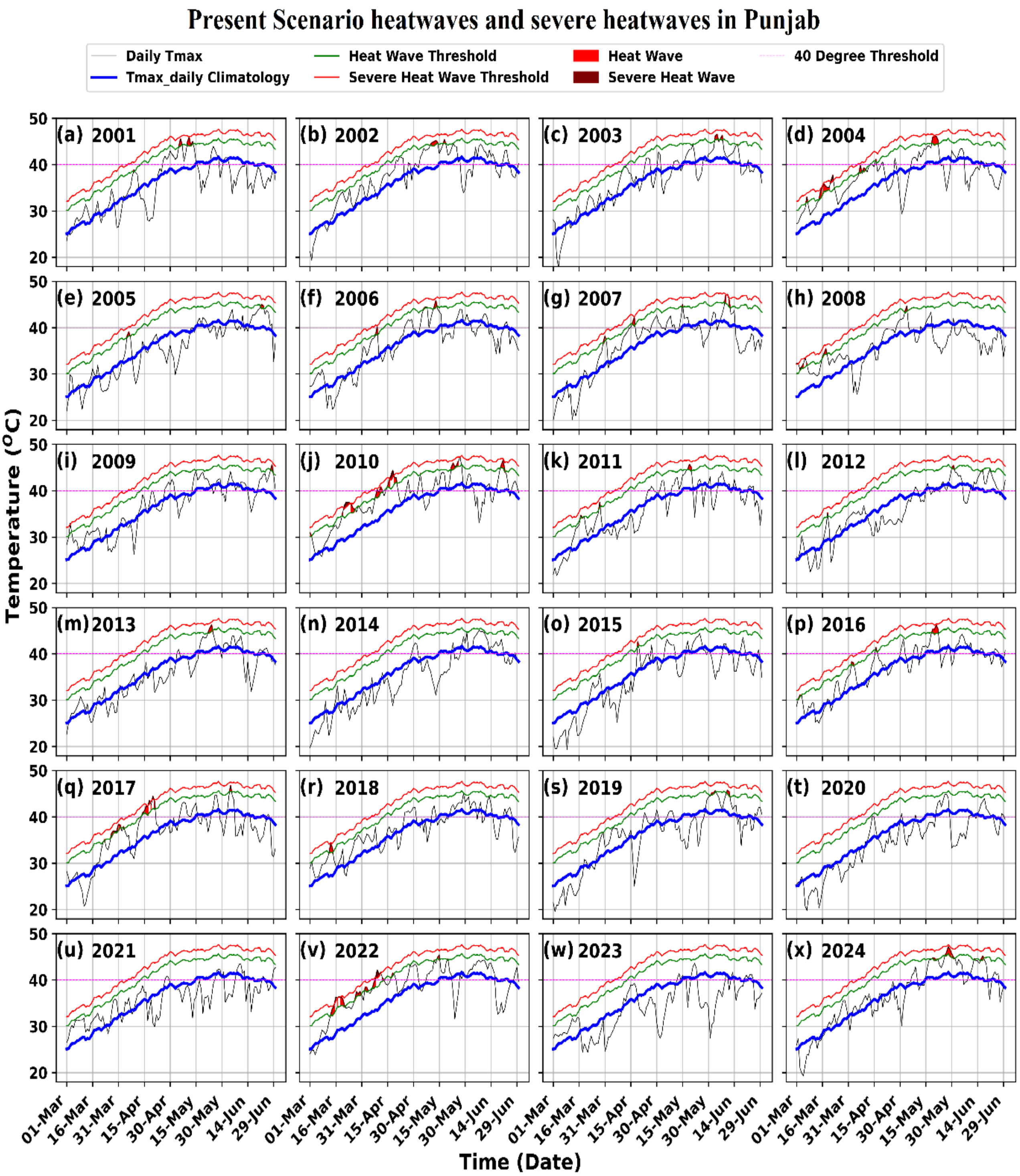

Figure 4. Yearly Variations of Heatwave (Mark Red) and Severe Heatwave (Mark Magenta) for the Present Scenario ((**a**)–(**x**): 2001–2024) for the Summer Months (March–June) for Punjab. The Meaning of the Colour Lines is Provided in the Legend at the Top.

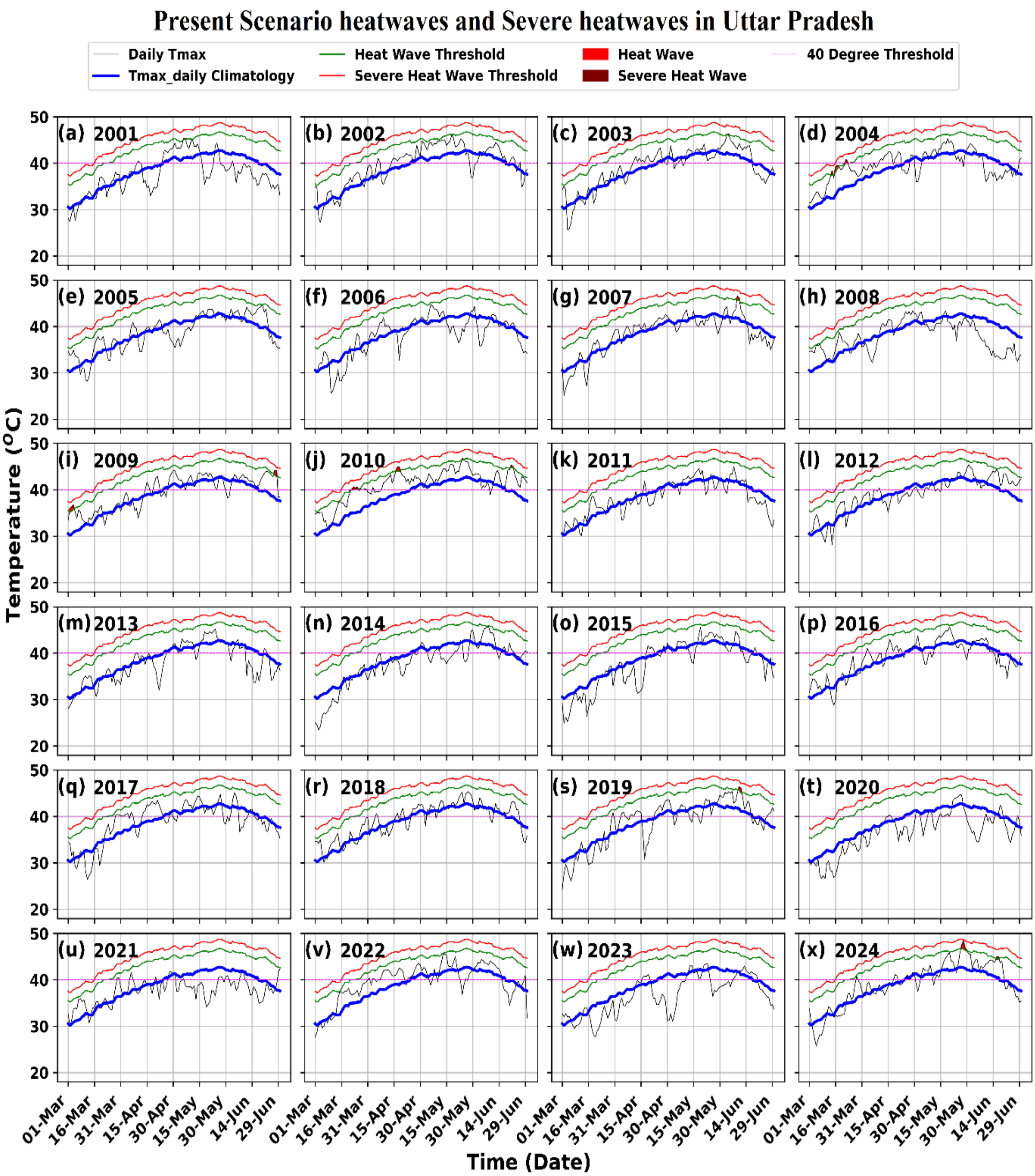

Figure 5. Yearly Variations of Heatwave (Mark Red) and Severe Heatwave (Mark Magenta) for the Present Scenario ((**a**)–(**x**): 2001–2024) for the Summer Months (March–June) for Uttar Pradesh. The Meaning of the Colour Lines is Provided in the Legend at the Top.

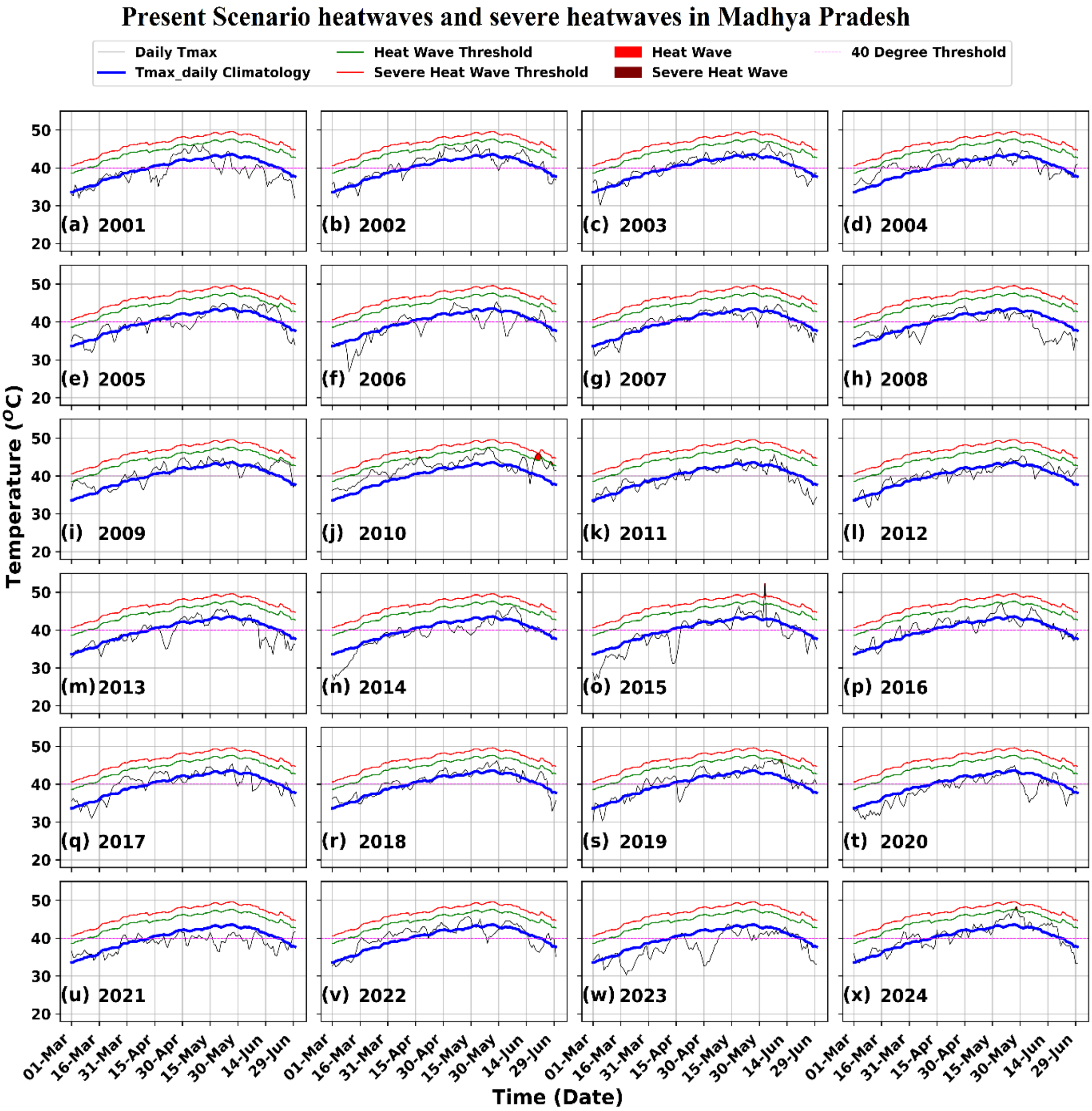

Figure 6. Yearly variations of heatwave (mark red) and severe heatwave (mark magenta) for the Present Scenario ((**a**)–(**x**): 2001–2024) for the Summer Months (March–June) for Madhya Pradesh. The Meaning of the Colour Lines is Provided in the Legend at the Top.

Figure 2 shows the monthly variations of T_{max}, heatwaves, and severe heatwaves for the Delhi region in the summer months (March–June). In **Figure 2a–c**, where the maximum temperature was captured starting in the middle of April and reached the threshold of 4 to 5 degrees Celsius above the normal of T_{max} in May, which is when a heatwave occurred. There has been a variation in the pattern in 2004, with heatwaves being detected in March (**Figure 2d**) and meeting the criteria of the normal of maximum temperature less than 40 °C as mentioned in **Table 1**. The heatwave occurrence happened in March and followed the same patterns of heatwaves in **Figure 2a–c** when compared to previous years for May. As stated above, the maximum temperature for 2005 (**Figure 2e**) showed a significant decline. The heatwaves were observed in June and met the criteria of the normal of maximum temperature less than 40 °C. For 2006 (**Figure 2f**), the highest temperature was recorded above 40 °C and there was a heatwave, but a significant drop in temperature was observed in June. **Figure 2g** demonstrates that in 2007, the maximum temperature began to decline in early March and endured heatwaves in June and there is a frequent rise that has been observed for heatwaves when the normal maximum temperature is less than 40 °C, but the value of maximum temperature has reached approximately 45 °C. During 2008 (**Figure 2h**), a heatwave occurred in March, and a drop-in temperature was seen in mid-May, which was below 40 °C.

At the beginning of 2009 (**Figure 2i**), the highest temperature was recorded in March. This was followed by a change in the number of heatwaves, which occurred in June. In March 2010 (**Figure 2j**), more episodes of heatwaves and severe heatwaves were observed, particularly during April, May, and June. In May 2011 (**Figure 2k**), a high temperature of more than 40 °C and the normal maximum temperature is also approaching 40 °C. At the end of May and June 2012 (**Figure 2l**), there was a heatwave, with a high temperature of more than 40 °C fulfilling the criteria of the normal of maximum temperature less than and greater than 40 °C. In 2013, temperatures reached a maximum temperature of 45 °C and a heatwave in May (**Figure 2m**) when the normal of T_{max} is ~40°C. Heatwave also hit in the middle of June 2014, as seen in **Figure 2n**, changing the pattern of temperature. For **Figure 2o** in May of 2015, as in previous years, there was a regular increase in temperature, and in June, there was a significant fall. The frequency of the highest temperature increased in April 2016 (**Figure 2p**). However, 2017 shows that heatwaves with temperatures over 40 °C occurred in April and June (**Figure 2q**). **Figure 2r** shows that in 2018 there was a quick change in weather conditions, and heatwave episode was recorded in March for low temperatures under 40 °C. During 2019 (**Figure 2s**) and 2023 (**Figure 2w**) show no heatwave event, but heatwave events are observed in 2020 (**Figure 2t**) during May, in 2021 (**Figure 2u**) during March, and in 2022 (**Figure 2v**) during March and April. Heatwave events are also observed in May and June during 2024 (**Figure 2x**).

Heatwaves and severe heatwaves, along with maximum temperature variations for West Bengal, are shown in **Figure 3**. The climatological maximum temperatures began to decline in early March (**Figure 3a**) for all the years. In April, maximum temperatures were frequently rising and had reached 40 °C. This was followed by a sharp decline in maximum temperatures in June (**Figure 3b**). When the highest temperature reached 45 °C, in contrast to the normal maximum temperature of less than 40 °C, a heatwave was noticed. The occurrence of a heatwave for 2003 (**Figure 3c**) is nearly identical to that in 2002 (**Figure 3b**). For 2004 (**Figure 3d**), the onset of heatwaves has been moved to March, where the maximum temperature is higher than the normal of maximum temperature and followed the deviation of 5 °C from the normal of maximum temperature was observed (**Figure 3e**). A sudden drop in maximum temperature was seen in the middle of April, and a heatwave was seen in the middle of May, followed by episodes of severe heatwaves, which reached a deviation of 7 °C from the normal of maximum temperature less than 40 °C.

Figure 3f shows that no heatwaves occurred in 2006; instead, the maximum temperature rose in April. **Figure 3g** shows instances of heatwaves that occurred in June of 2007 and had maximum temperatures of more than 40 °C. According to the normal maximum temperature, no heatwaves have been reported for 2008 (**Figure 3h**), 2011 (**Figure 3k**), and 2013 (**Figure 3m**) but a heatwave occurred in 2014 (**Figure 3n**). The pattern of heatwave occurrence has changed, peaking during June with severe heatwaves in 2009 (**Figure 3i**). The more frequent heatwaves between April and the end of June had been accompanied by a rapid drop in maximum temperature observed in 2010 (**Figure 3j**). In 2012 (**Figure 3l**), heatwaves are more common in June and early July, when the normal of maximum temperature is below 40 °C. In 2015 (**Figure 3o**), the occurrence of heatwaves was observed in June when the normal maximum temperature was less than 40 °C. For 2016 and 2018, a frequent rise in temperature in May and June has been experienced as shown in (**Figure 3p–r**). Heatwave during 2019 (**Figure 3s**) is observed in June only. There is no heatwave event in 2020 (**Figure 3t**). Heatwave events are observed during mid-April in 2021 (**Figure 3u**), during end of April and mid-June in 2022 (**Figure 3v**), but severe heatwaves occurred during June in 2023 (**Figure 3w**) and 2024 (**Figure 3x**). Therefore, in the case of West Bengal, most of the heatwaves have happened based on the normal of maximum temperatures less than 40 °C, but the values of maximum temperatures are rising extremely regularly and are getting close to 45 °C.

The variations of heatwaves and severe heatwaves for different years (2001–2024) in the Punjab region are shown in **Figure 4**. During 2001 and 2002, when the normal maximum temperature was higher than 40 °C and the maximum temperature was close to 40 °C in May, there was almost a comparable change in the pattern as highlighted in both years (**Figure 4a,b**). As indicated in **Figure 4c**, the frequency of heatwaves in 2003 has altered and been transferred to June compared to 2002, when temperatures typically reach beyond 40 °C. The occurrence of heatwaves has been noticed in March and May for all the years analysed here, but when compared to 2003 (**Figure 4c**), a sharp decline in the maximum temperature has been observed as reflected in 2004 (**Figure 4d**). For, 2005 a sharp decline in the temperature for May has been observed for heatwave in June in 2005 (**Figure 4e**). As demonstrated in (**Figure 4f**), 2006 saw a rise in the maximum temperature combined with a heatwave in April and May. In 2007, the heatwave began in the middle of April (**Figure 4g**), where the average maximum temperature is less than 40 °C. Heatwaves occurred in March in each of the years 2008 and 2019; following this, the maximum temperature has increased (**Figure 4h,i**). The severity of heatwave events from March to June has been approaching, with many episodes of severe heatwaves observed in April and May, characterised by frequent temperature rises to 45°C, as captured in 2010 (**Figure 4j**).

It has been observed that during the years (2011–2013), heatwaves were observed in May (**Figure 4k–m**), where the normal maximum temperature is greater than 40 °C. For the years 2014 and 2015, almost similar changes in maximum temperature along with heatwaves were observed for 2014 in June (**Figure 4n**) and at the end of April in 2015 (**Figure 4o**). In 2016, Punjab experienced a heatwave during mid-May when the value of maximum temperature approaching 45°C (**Figure 4p**). A frequent rise in temperature has been observed for heatwave during April and May followed by severe heatwave conditions (**Figure 4q**) in 2017. Increased intensity of heatwave in March along with the rising temperature followed by heatwave in May are observed in 2018 (**Figure 4r**). Almost negligible heatwave events are observed in 2020 (**Figure 4t**), 2021 (**Figure 4u**) and 2023 (**Figure 4w**), but number of heatwaves and severe heatwaves observed during March to April in 2022 (**Figure 4v**), and during May to June in 2019 (**Figure 4s**) and 2024 (**Figure 4x**). Therefore, in the case of Punjab, most heatwaves have happened based on the normal of maximum temperatures more than 40 °C, and the values of maximum temperatures are rising extremely regularly and are getting close to 45°C.

The monthly variations of maximum temperature, heatwave, and severe heatwaves for Uttar Pradesh are shown in **Figure 5**. The years, 2001 and 2002, experienced the same temperature change in May and June, where the value of maximum temperature and normal maximum temperature is greater than 40 °C (**Figure 5a,b).** The temperature started rising in April 2003 when the maximum temperature approached 45°C and a heatwave was experienced in June (**Figure 5c**). For 2004, March experienced heatwaves based on a maximum temperature approaching 40 °C and a temperature rise experienced in the starting of June month (**Figure 5d**). A declining pattern of maximum temperature in May and an increasing pattern of temperature for June where the value of normal of maximum temperature crossed 40 °C for 2005 (**Figure 5e**). A frequent rise in the mid of April and May has been observed, where the normal of maximum temperature is more than 40 °C for 2006 (**Figure 5f**).

In 2007, an increase in temperature of more than 45 °C for June and has been observed and a heatwave occurred based on the deviation of 5 °C from the normal maximum temperature (**Figure 5g**). Consecutively, 2008 (**Figure 5h**) experienced maximum temperature in April and a declining pattern of maximum temperature has been observed based on the normal of maximum temperature and 2009 has shown variability in the maximum temperature and has attained the maximum temperature for June contributing to the heatwave (**Figure 5i**). The most frequent heatwaves for all the months had occurred in 2010 (**Figure 5j**), where the value of maximum temperature has approached more than 45 °C in mid-April and persists during May and June. A declining maximum temperature pattern has been observed (**Figure 5k,l**) and for 2012, a rise in maximum temperature of more than 40 °C was observed in June. Furthermore, for 2013 a frequent decrease in maximum temperature was observed in mid-April followed by an increase in mid-May (**Figure 5m**); for 2014, again a frequent rise in temperature was observed at the start of May an increase in temperature up to 45 °C has been observed followed by a heatwave in mid-June (**Figure 5n**). For year 2015, a declining pattern in the maximum heatwaves has been observed. A steep increase for 2016 has been observed based on the normal Maximum Temperature and has attained 45°C mid-May (**Figure 5p**). In comparison to (**Figure 5n–p**), an increasing pattern of maximum temperature has been observed for 2017 in April (**Figure 5q**). For 2018, in mid-May, the maximum temperature has obtained the same value as the normal of maximum temperature, followed by frequent rise in maximum temperature (**Figure 5r**). No heatwaves are observed during the years 2015–2018 (**Figure 5o–r**) and 2020–2023 (**Figure 5t–w**). Heatwave events were observed during mid-June in 2019 (**Figure 5s**) but in 2024 it is observed during April, June and the end of May (**Figure 5x**). Therefore, in the case of Uttar Pradesh, most heatwaves have happened based on the normal of maximum temperatures more than 40 °C, and the values of maximum temperatures are rising extremely regularly and are getting close to 45 °C.

For the Madhya Pradesh state (**Figure 6**), the maximum temperature from 2001, along with that climatology, has experienced the heatwave based on maximum temperature more than 40 °C (**Figure 6a**) and has shown the different variability when compared with Punjab (**Figure 4a**) and Delhi (**Figure 2a**). For 2002, the maximum temperature has been increased to 40 °C in June, and it has been reported that maximum variations in temperature frequently occur following the same pattern that accompanied the 2001 heatwave (**Figure 6b**). For the month of June, a maximum temperature of 45 °C was reached (**Figure 6c**). From March through June in 2004, the maximum temperature increased significantly (**Figure 6d**). The same temperature pattern was shown for March and April as well, with a dramatic rise in temperatures in June and a subsequent heatwave (**Figure 6e**). Following the severity of the peak temperatures in mid-May and mid-June, a dramatic fall in temperature for March has been noted for 2006 (**Figure 6f**). For the year 2007, the maximum temperature has gotten close to the maximum temperature climatology, then dropped significantly in June (**Figure 6g**). Maximum Temperature of more than 40 °C has been observed in April and May followed by a sharp decline in the maximum temperature for the month of June (**Figure 6h**). A sudden rise in temperature has been recorded for 2009, with the highest temperature recorded for the month of June exceeding 45°C and being followed by a heatwave (**Figure 6i**).

In contrast to Punjab and Delhi, Madhya Pradesh had a heatwave in the middle of April, mid-May, and June based on a deviation from the average of maximum temperatures of more than 40 °C for 2010 (**Figure 6j**). A similar pattern of maximum temperature matching maximum temperature climatology has been seen in 2011 (**Figure 6k**), which was followed by an abrupt decline in temperature in June. A considerable increase in the maximum temperature for the month of June has been seen, along with a similar pattern of temperature through March and April as in 2012 (**Figure 6l**). May experienced a strong rise in temperature, which was followed by a sharp rise in temperatures for the entire year of 2013 (**Figure 6m**). The highest temperature for 2014 has been getting closer to 45°C since April (**Figure 6n**). However, a severe heatwave in 2015 occurred when the highest temperature has attained 45°C and deviation from normal of maximum temperature has been observed (**Figure 6o**). In Madhya Pradesh, during 2016 compared to the other years indicated above, heatwaves occurred since they exceed 40 °C at their highest (**Figure 6p**). No heatwave events occurred during the years 2017–2018 (**Figure 6q,r**) and 2020–2023 (**Figure 6t–w**), but it occurred in 2019 during mid-June (**Figure 6s**) and in 2024 during end of May (**Figure 6x**). Therefore, in the case of Madhya Pradesh, most heatwaves have happened based on the normal of maximum temperatures more than 40 °C, and the values of maximum temperatures are rising extremely regularly and are getting close to 45 °C.

Andhra Pradesh witnessed its highest temperature on record beginning in 2001 (**Figure 7a**). Additionally, the state's climatology recorded a heatwave based on a maximum temperature of more than 40 °C, and it showed distinct variability when compared to other states considered for the study. Andhra Pradesh is meeting the IMD criterion for heatwaves based on actual maximum temperature, exhibiting the climatology of maximum temperatures beginning above 35°C and reaching 40 °C starting in April. Although Andhra Pradesh experienced similar patterns in maximum temperatures for 2002, the state was labelled as experiencing a heatwave in May after exceeding the normal maximum temperature range of 4 to 5 °C (**Figure 7b**). Similarly, for years 2003 and 2005, heatwaves have occurred in June and have also attained the maximum temperature more than 40 °C and 4 °C to 5 °C deviation from normal of maximum temperature (**Figure 7c,e**). A severe decline in the maximum temperature of May has been observed based on the climatology of maximum temperature for 2004 (**Figure 7d**). An increase in the maximum temperature based on the climatology has been observed for 2006–2007 followed by a sharp decline in the maximum temperature for June (**Figure 7f,g**). Considering, 2008 in comparison to the previous years, a sharp decline in maximum temperature has been observed for March and June (**Figure 7h**). A changing pattern of maximum temperature has been observed and the occurrence of heatwaves in June along with the rise in maximum temperature has been noticed for 2009 (**Figure 7i**). 2010 and 2011 (**Figure 7j,k**) attained the same maximum temperature same as the normal of maximum temperature in May, followed by a declining pattern of maximum temperature for June based on the normal of maximum temperature. Again, the variation for 2012 (**Figure 7l**) has been observed where the value of maximum temperature has approached 45 °C and had experienced a heatwave in June based on the normal maximum temperature equal to 40 °C. A step increase in the maximum temperature was observed in mid-May and then followed the declining pattern of maximum temperature for June month for 2013 (**Figure 7m**). A decline in maximum temperature has been observed followed by an increase in the maximum temperature for 2014 (**Figure 7n**). A distinct temperature pattern has been observed for 2015, and the heatwave has been noticed when the normal of maximum temperature is more than 40 °C along with maximum temperature (**Figure 7o**). A frequent rise in temperature based on climatology has been noticed for March, April and May followed by a declining pattern in June for (**Figure 7p**). For the years 2017–2018, the maximum temperature has approached the normal of maximum temperature and has shown the rise in May (**Figure 7q,r**). Several heatwave events were observed in 2019 (**Figure 7s**) throughout the summer months. Few events are observed during the years 2020–2023 (**Figure 7t–w**). During the summer months of 2024, a series of heatwave and severe heatwave events occurred (**Figure 7x**). Most heatwaves that happened in the state of Andhra Pradesh are based on the normal maximum temperatures is less than 40 °C, and the values of maximum temperatures are rising extremely regularly and are getting close to 45 °C.

Analysis of spatial variations of Tmax shows that the maximum temperature is below 40 °C during March for Delhi, Punjab, Uttar Pradesh, and Madhya Pradesh in the present scenario but in the future scenarios, it is more than 40 °C for all the above states except Delhi (**Figures 8a–c**, **9a–c**, **10a–c**, and **11(a–c)**). During the other summer months (April–June) for all scenario temperatures near or more than 40 °C (**Figures 8** and **12b**,**c**). West Bengal and Andhra Pradesh show temperatures near or more than 40 °C for all the summer months for all scenarios (**Figures 12a–c** and **13a–c**). It is to be noted that maximum temperature increases for all the summer months and nearing or more than 40 °C for all states except March for Delhi for future scenarios (**Figure 8b**, **c**) indicating that high-temperature summer months going to be longer and starts early in future scenarios for all the states except Delhi. Spatial variation of the trends of maximum temperature shows positive trends ranging from 0.01 °C/year to 0.3 °C/year for all the states for all the summer months in the future scenarios although negative trends are observed for the present scenario in March to May (**Supplementary Materials**, **Figures S1**–**S6**).

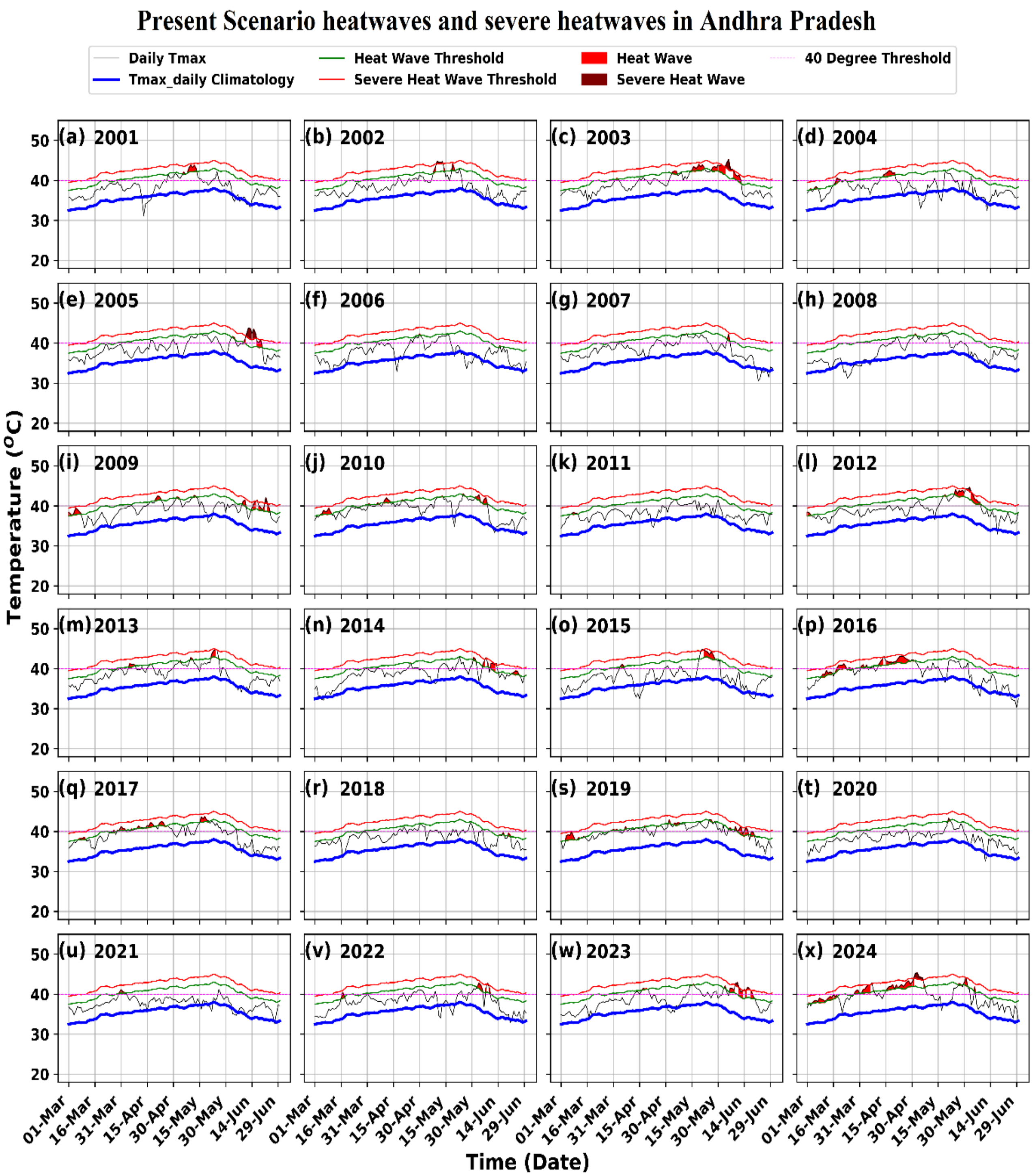

Figure 7. Yearly Variations of Heatwave (Mark Red) and Severe Heatwave (Mark Magenta) for the Present Scenario (**(a)**–**(x)**: 2001–2024) for the Summer Months (March–June) for Andhra Pradesh. The Meaning of the Colour Lines is Provided in the Legend at the Top.

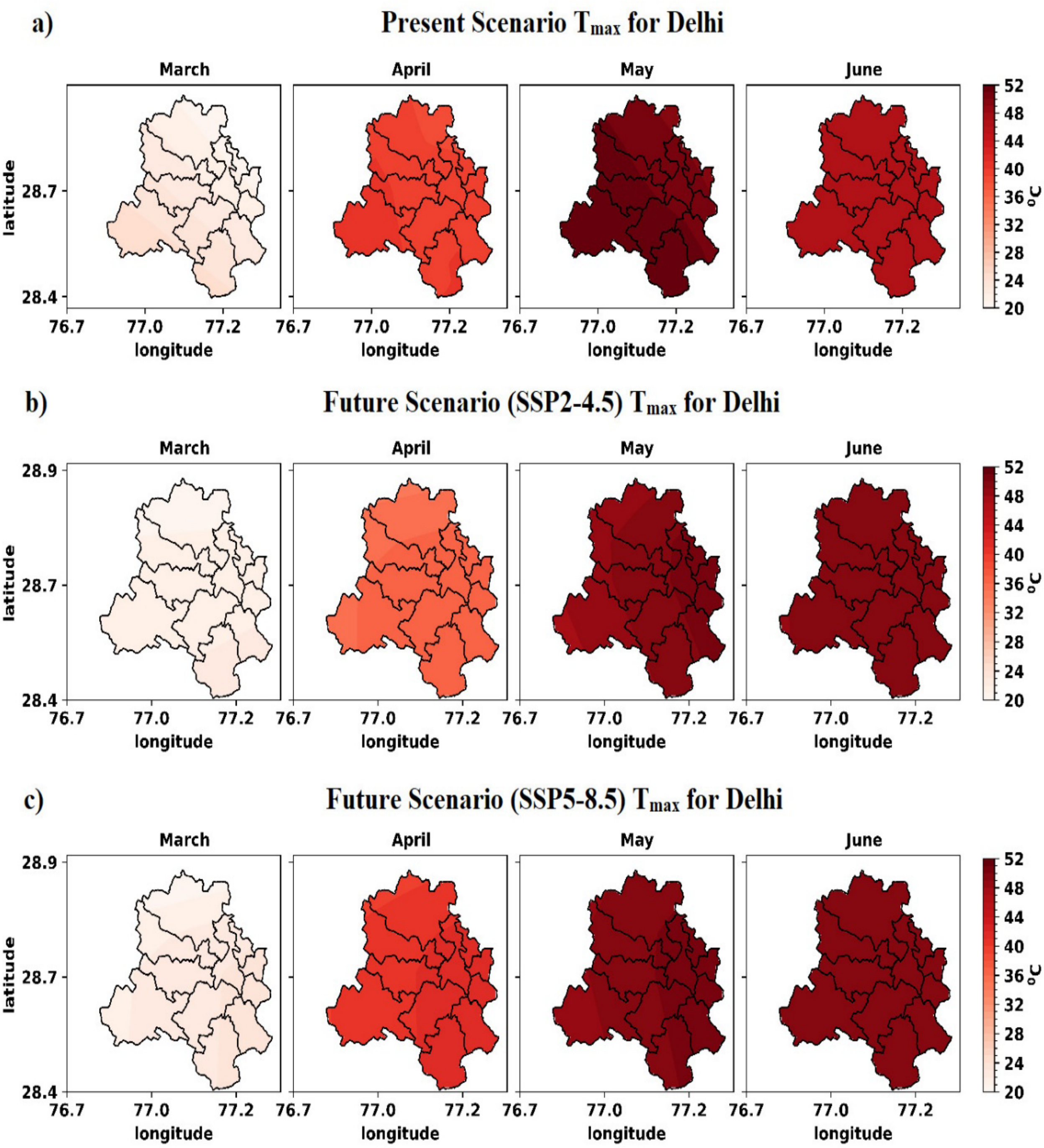

Figure 8. Maximum Temperature for March, April, May, and June from (**a**) Present, (**b**) Future SSP2-4.5, and **(c)** Future SSP5-8.5 Scenarios for the Delhi Region.

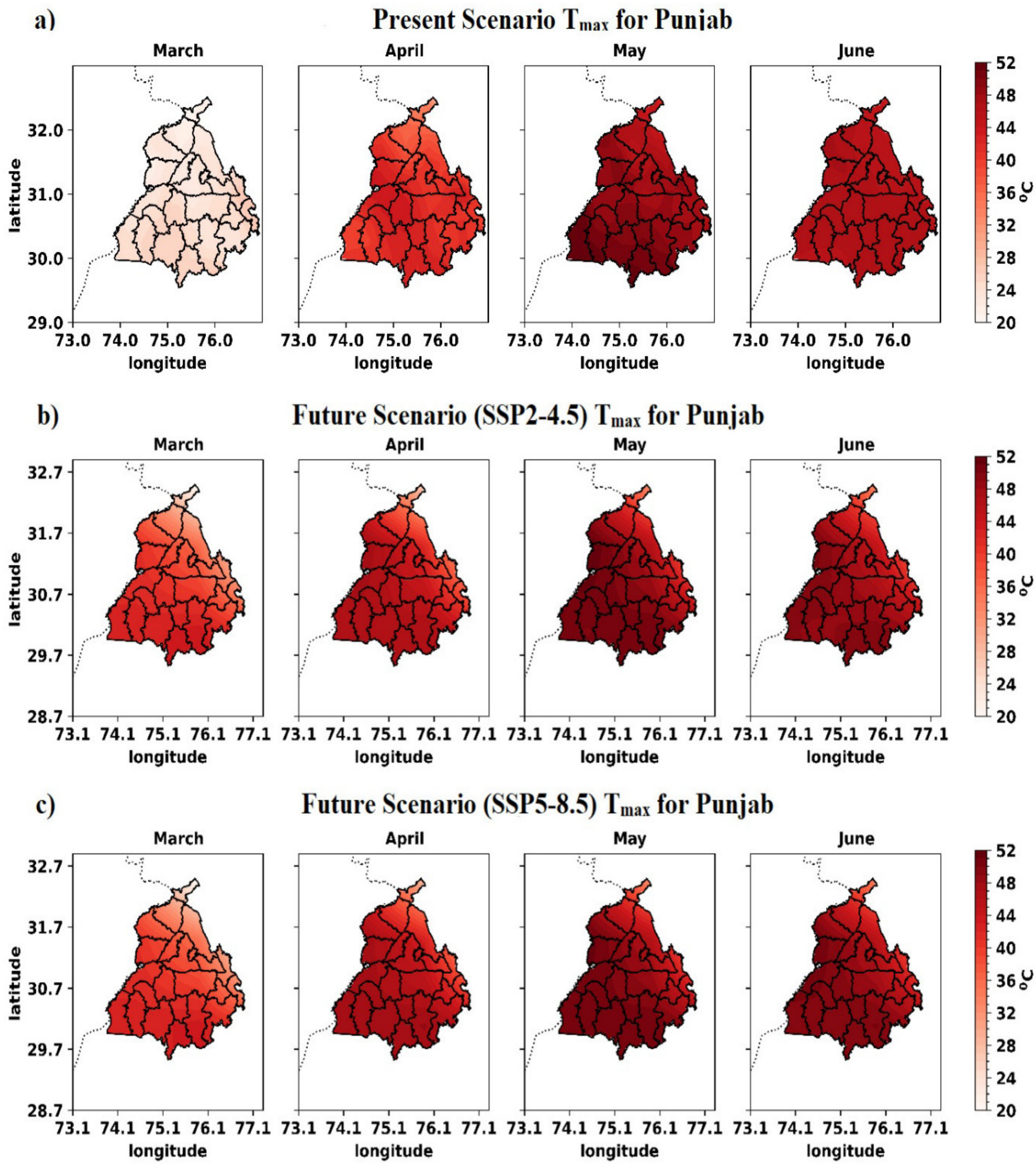

Figure 9. Maximum Temperature for March, April, May, and June from **(a)** Present, **(b)** Future SSP2-4.5, and **(c)** Future SSP5-8.5 Scenarios for the Punjab Region.

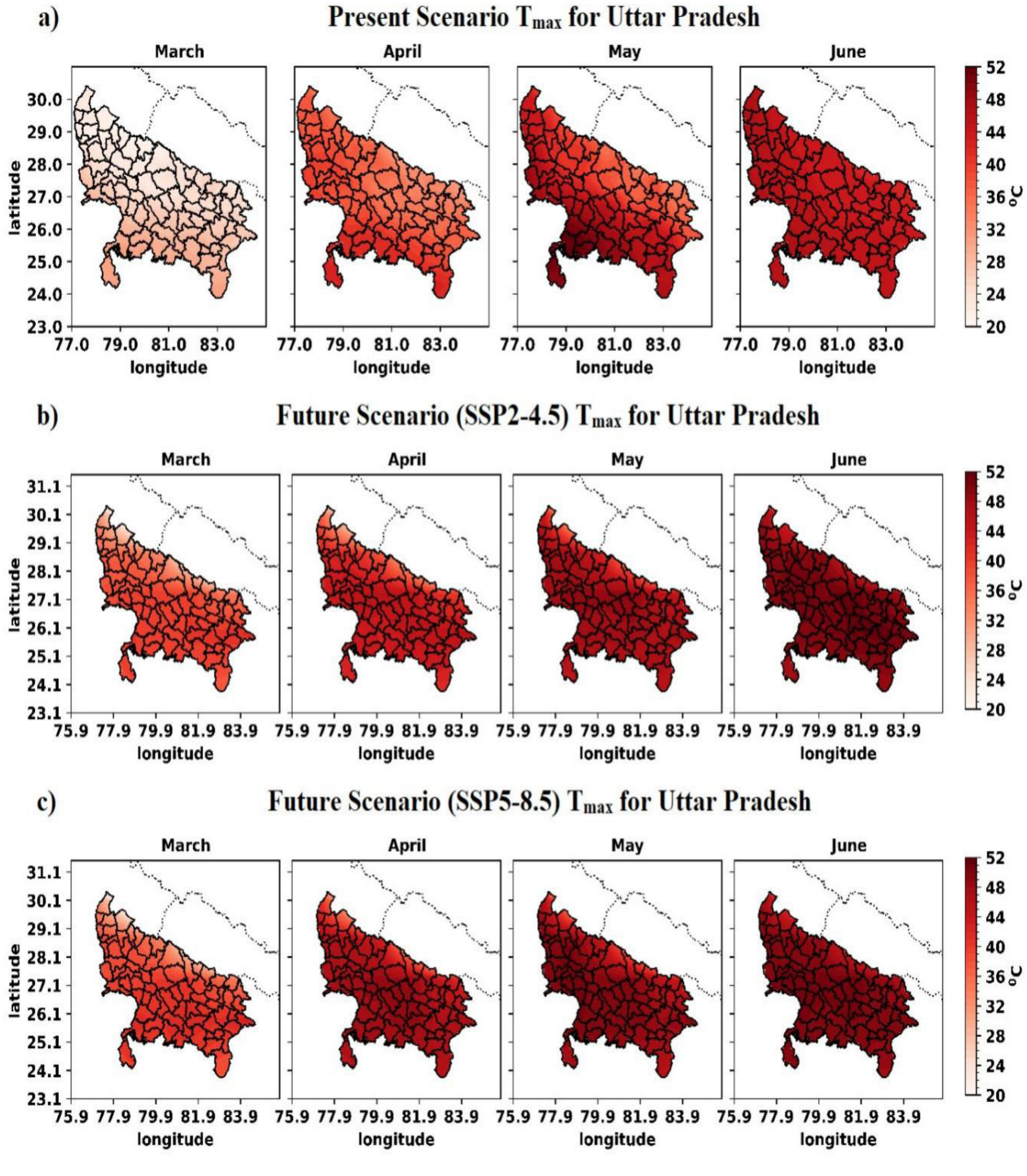

Figure 10. Maximum Temperature for March, April, May, and June from (**a**) Present, (**b**) Future SSP2-4.5, and **(c)** Future SSP5-8.5 Scenarios for the Uttar Pradesh Region.

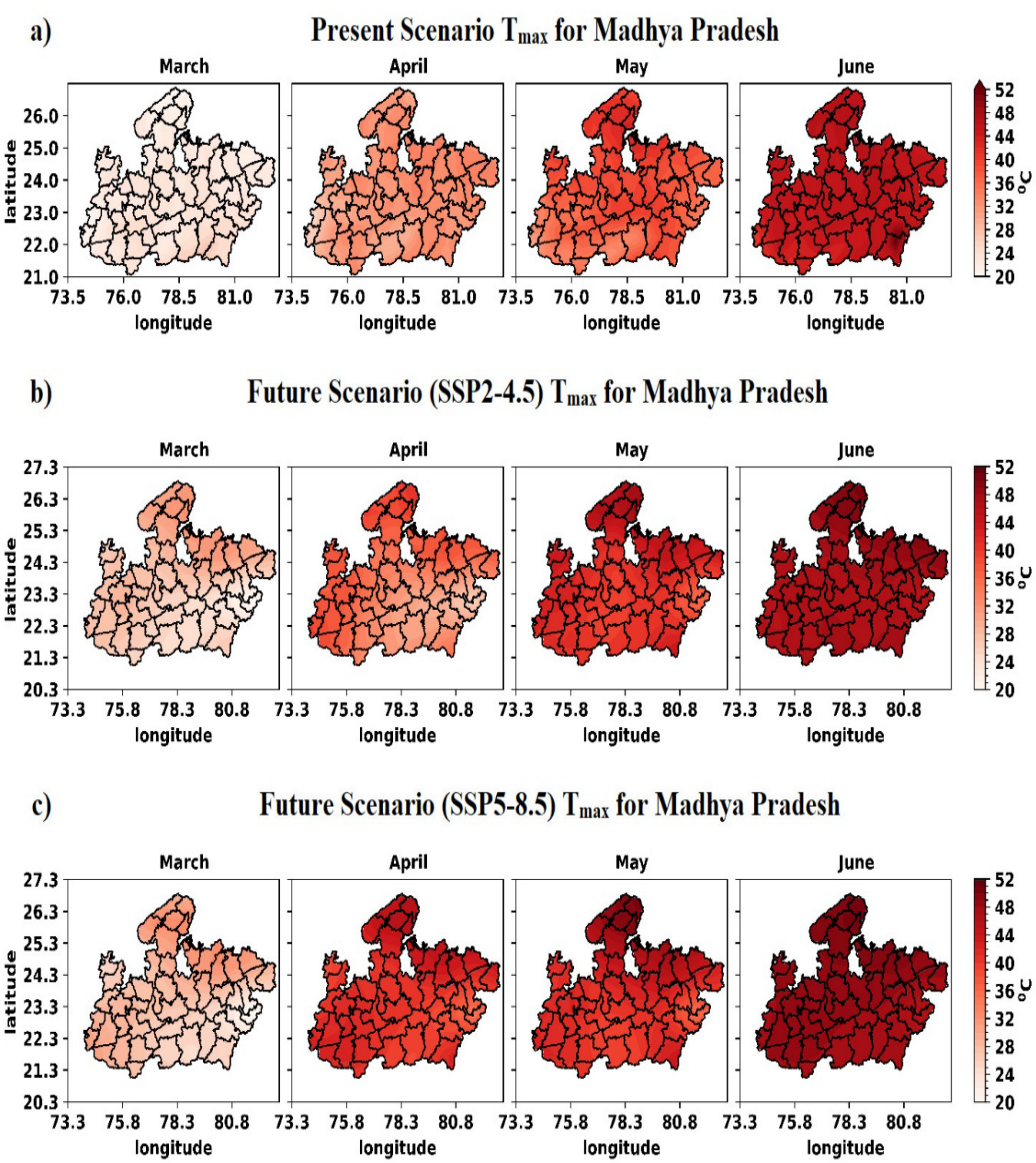

Figure 11. Maximum Temperature for March, April, May, and June from (**a**) Present, (**b**) Future SSP2-4.5, and **(c)** Future SSP5-8.5 Scenarios for the Madhya Pradesh Region.

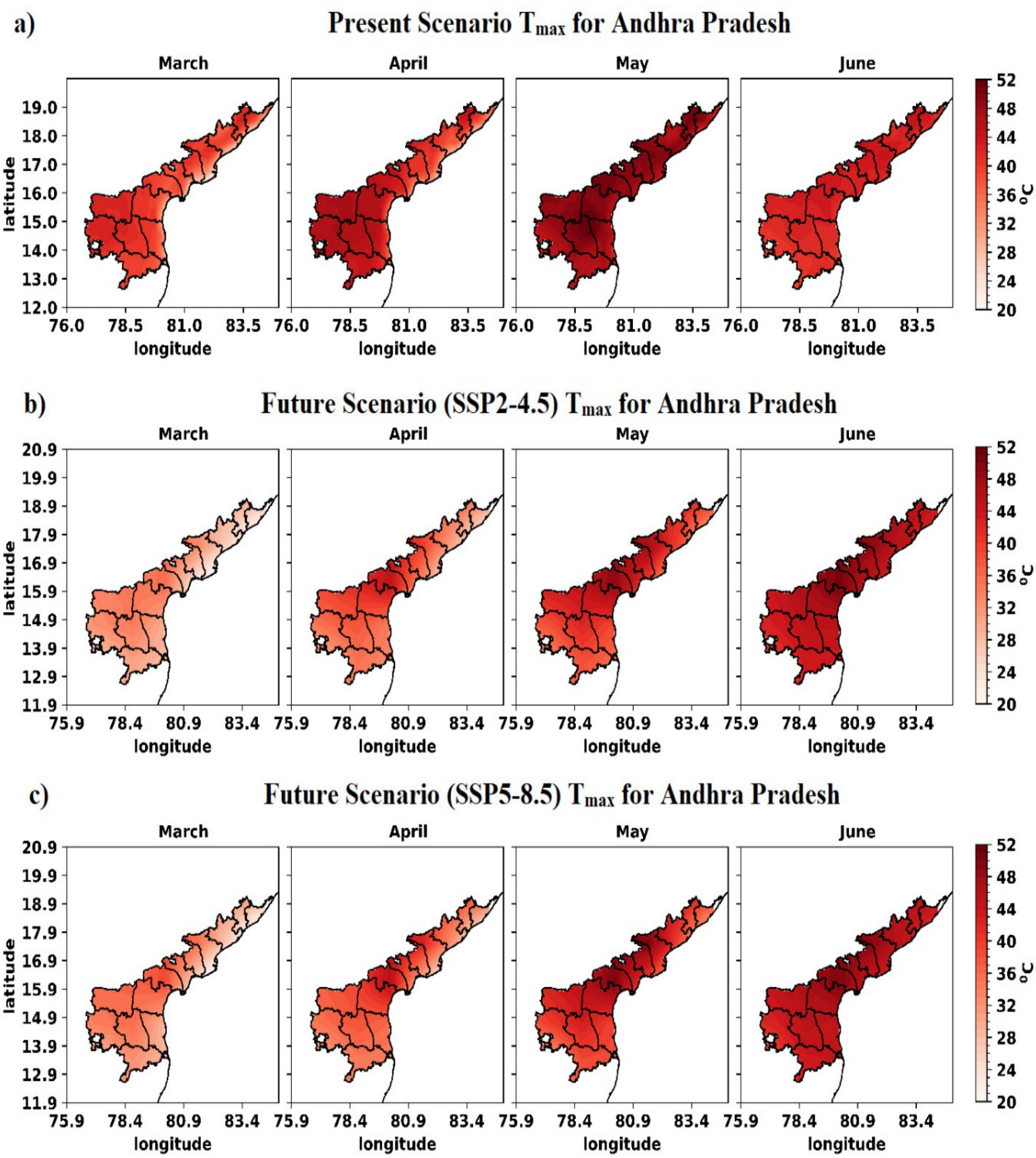

Figure 12. Maximum Temperature for March, April, May, and June from (**a**) Present, (**b**) Future SSP2-4.5, and **(c)** Future SSP5-8.5 Scenarios for the Andhra Pradesh Region.

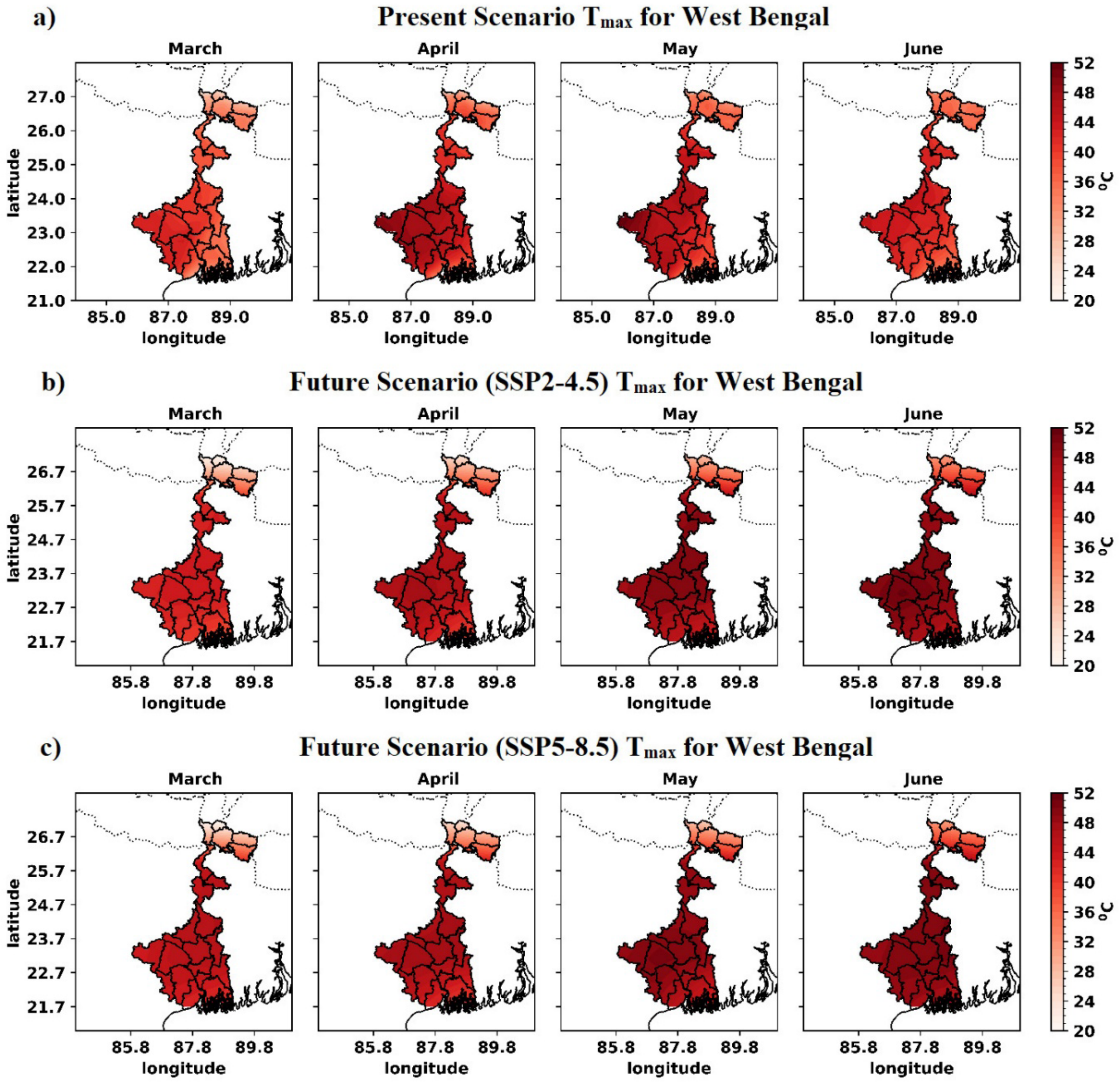

Figure 13. Maximum Temperature for March, April, May, and June from (**a**) Present, (**b**) Future SSP2-4.5, and **(c)** Future SSP5-8.5 Scenarios for the West Bengal Region.

Heatwave characteristics (frequency, duration, and intensity) were also investigated to understand the climate change impacts for the six Indian states of our study for the present scenario (**Figure 14**) and future SSP scenarios (**Figures 15a–f** & **16a–f**). In the present scenario, the maximum frequency of heatwaves is observed for Delhi, West Bengal, and Punjab (**Figure 14a–c**) but, less frequency is observed for Uttar Pradesh and Madhya Pradesh (**Figure 14d–e**). In the future SSP scenarios, the frequency of heatwaves increased for all the states with the highest in Delhi, followed by Punjab and Uttar Pradesh but the least in Andhra Pradesh (**Figures 15** & **16**). The duration of heatwaves in the present scenario is maximum for Punjab (**Figure 14c**) followed by Delhi, West Bengal, Andhra Pradesh, Uttar Pradesh, and Madhya Pradesh (**Figure 14a,b**,**d–f**). Duration of heatwaves increased for all the states for future scenarios with the highest for Delhi followed by West Bengal, Punjab, Uttar Pradesh, Madhya Pradesh, and Andhra Pradesh (**Figures 15** & **16**). The intensity of heatwaves ranges from 4 °C to 9 °C during present scenario with highest for Delhi followed by Punjab, West Bengal, Uttar Pradesh, Andhra Pradesh and Madhya Pradesh (**Figure 14**). But intensity ranges increased to 5 °C to 11 °C during future scenarios with highest for Punjab followed by Delhi, West Bengal, Uttar Pradesh, Madhya Pradesh and Andhra Pradesh (**Figures 15** & **16**).

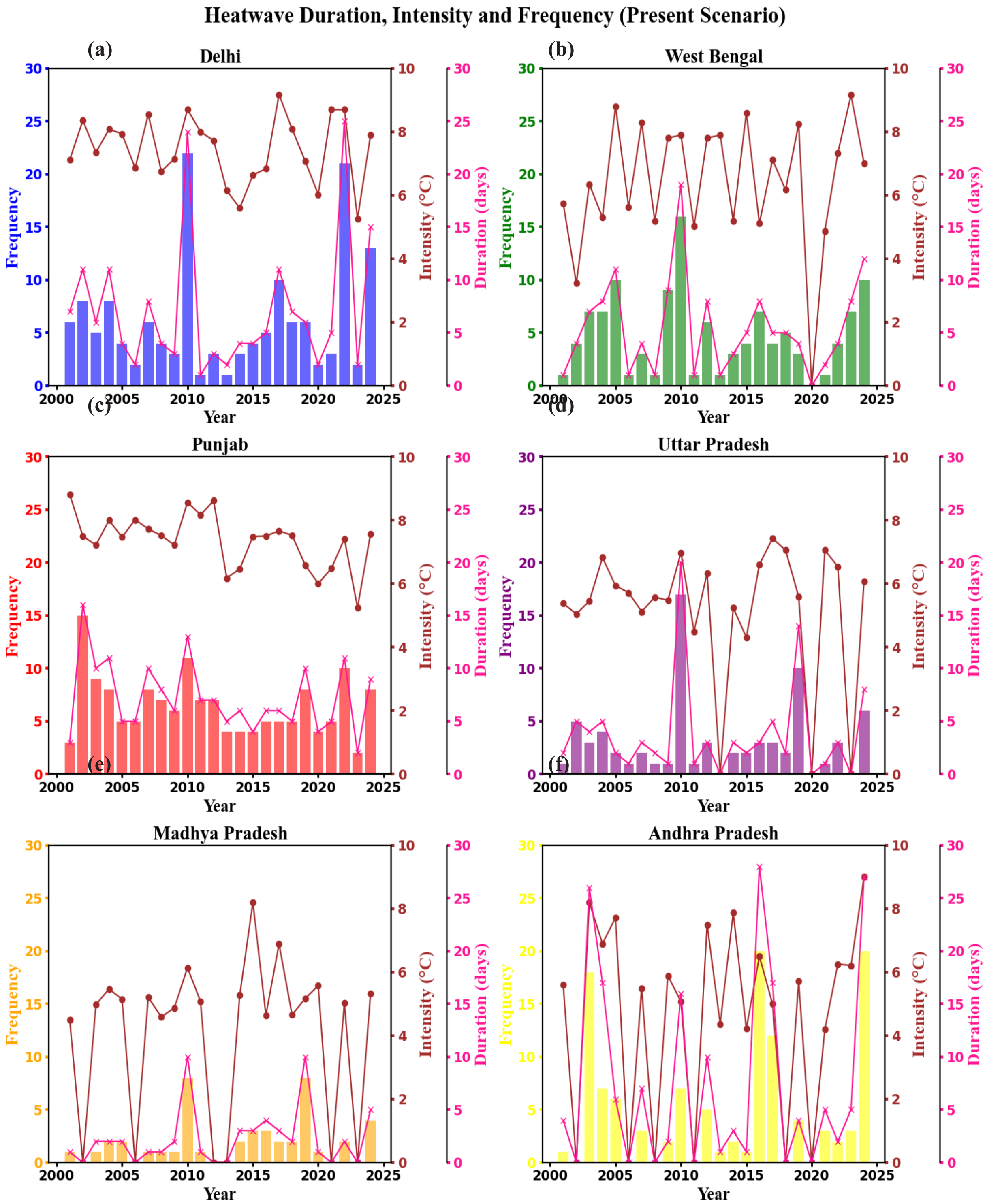

Figure 14. Yearly Variations of Present Scenario Heatwave Characteristics for the Six Different States ((**a**) Delhi, (**b**) West Bengal, (**c**) Punjab, (**d**) Uttar Pradesh, (**e**) Madhya Pradesh, and (**f**) Andhra Pradesh) of India During Summer Months.

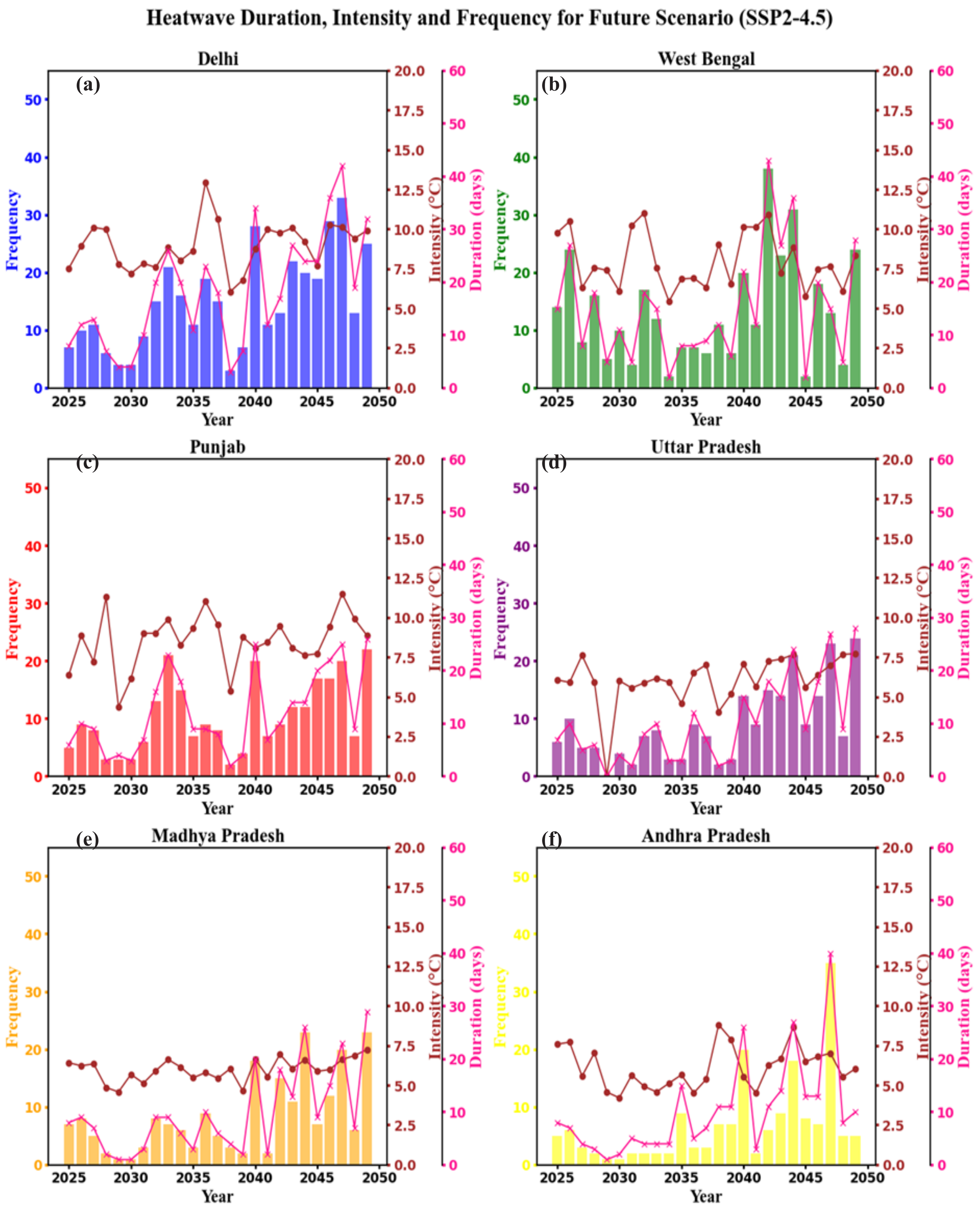

Figure 15. Yearly Variations of Future SSP2-4.5 Scenario Heatwave Characteristics for the Six Different States ((**a**) Delhi, (**b**) West Bengal, (**c**) Punjab, (**d**) Uttar Pradesh, (**e**) Madhya Pradesh, and (**f**) Andhra Pradesh) of India During Summer Months.

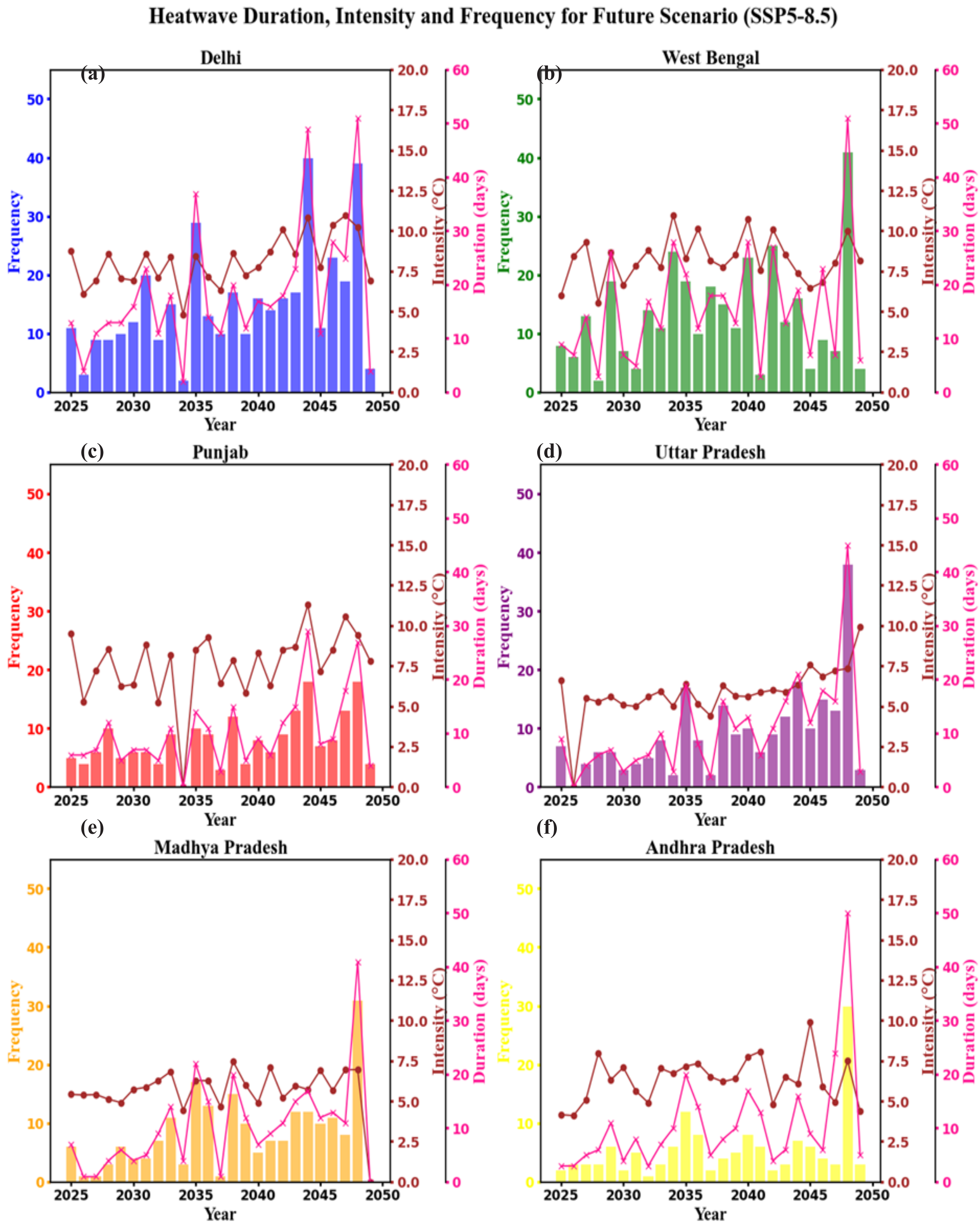

Figure 16. Yearly Variations of Future SSP5-8.5 Scenario Heatwave Characteristics for the Six Different States ((**a**) Delhi, (**b**) West Bengal, (**c**) Punjab, (**d**) Uttar Pradesh, (**e**) Madhya Pradesh, and (**f**) Andhra Pradesh) of India During Summer Months.

3.2. Heat Index (HI) Temperature and Heat Stress Categories

The heat index which is a measure of heat stress and the corresponding hazard level of heat stress categories (**Table 2**) for the six different cities of India are discussed here. The analysis was performed for the present as well as for the future scenarios of the summer months of March, April, May, and June. Average HI vulnerability for present (**Figure 17**) and future scenarios (**Figures 18 & 19**) are discussed for a better understanding of the heat stress category experienced by different Indian states of our study and may be useful for future planning. It is observed from the heat index during summer that heat-related vulnerability can go from caution to extreme caution states for the Delhi region. Extreme caution is observed during June. A similar case can be observed in West Bengal, but extreme caution is observed from April. Caution to extreme caution conditions are observed for Punjab, Uttar Pradesh, and Madhya Pradesh, similar to those in the Delhi region. Andhra Pradesh region experiences extreme caution to Danger conditions.

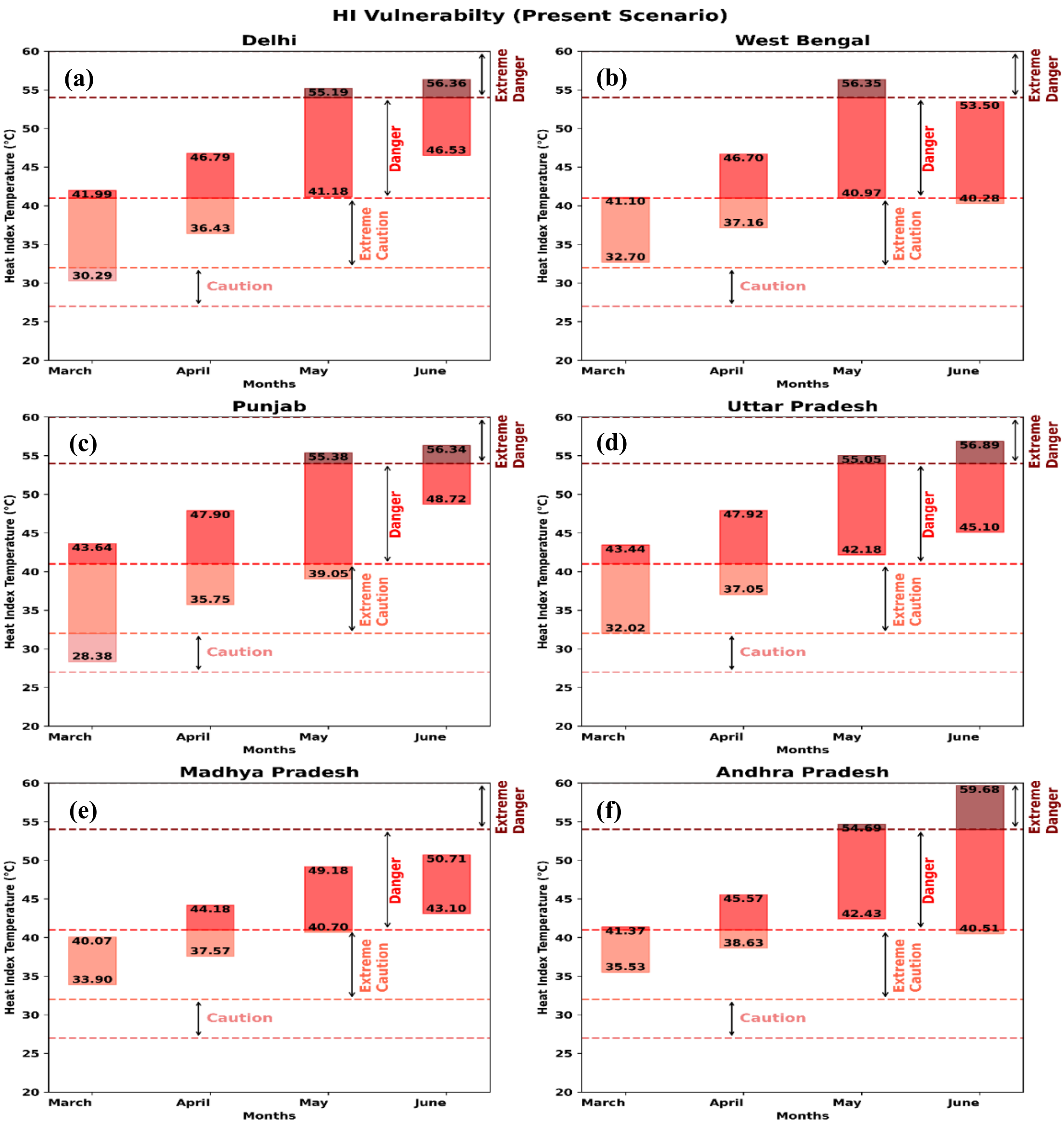

Figure 17. Present Scenario HI Vulnerability of the Summer Months for (**a**) Delhi, (**b**) West Bengal, (**c**) Punjab, (**d**) Uttar Pradesh, (**e**) Madhya Pradesh, and (**f**) Andhra Pradesh.

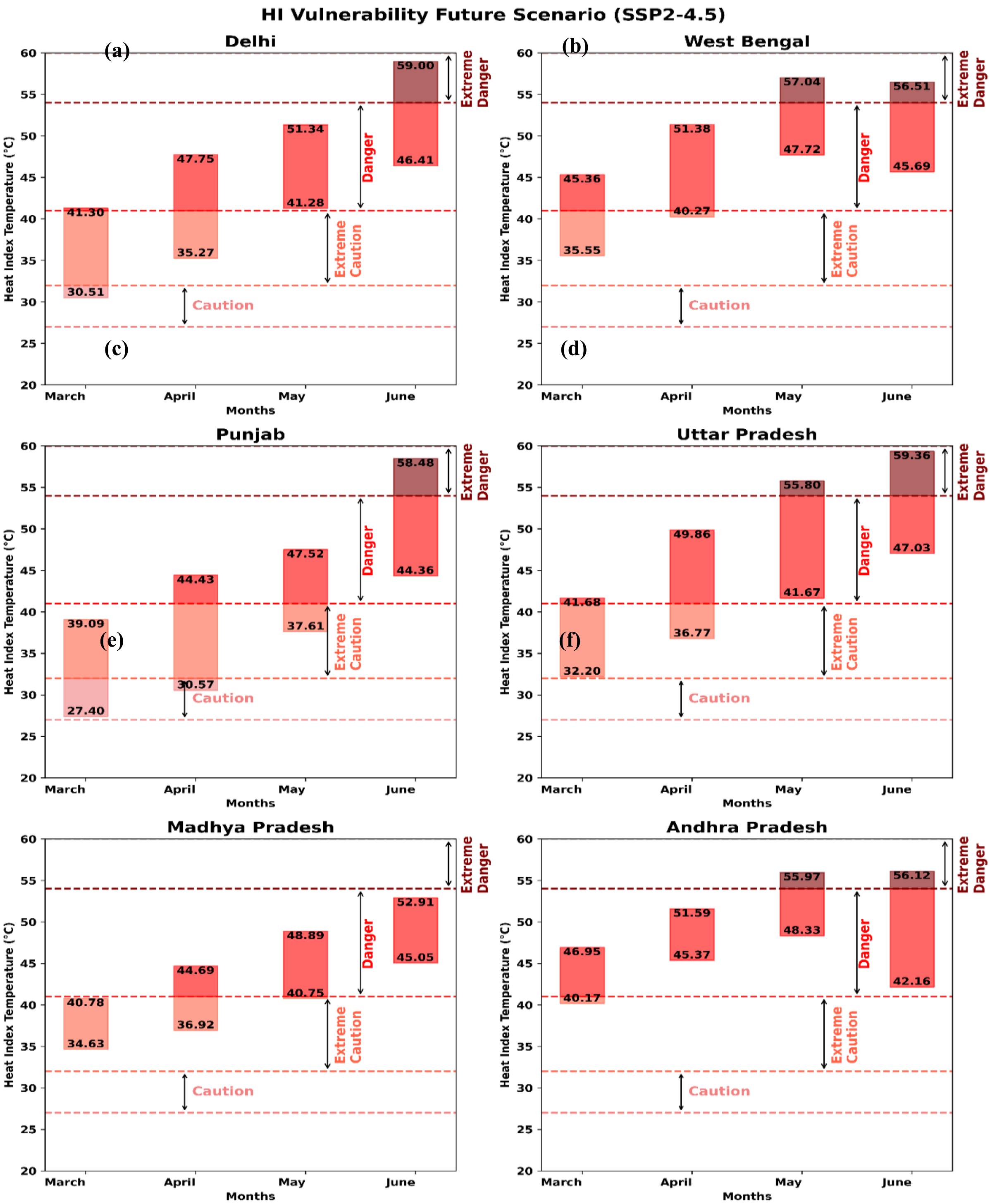

Figure 18. Future SSP2-4.5 Scenario HI Vulnerability of the Summer Months for (**a**) Delhi, (**b**) West Bengal, (**c**) Punjab, (**d**) Uttar Pradesh, (**e**) Madhya Pradesh, and (**f**) Andhra Pradesh.

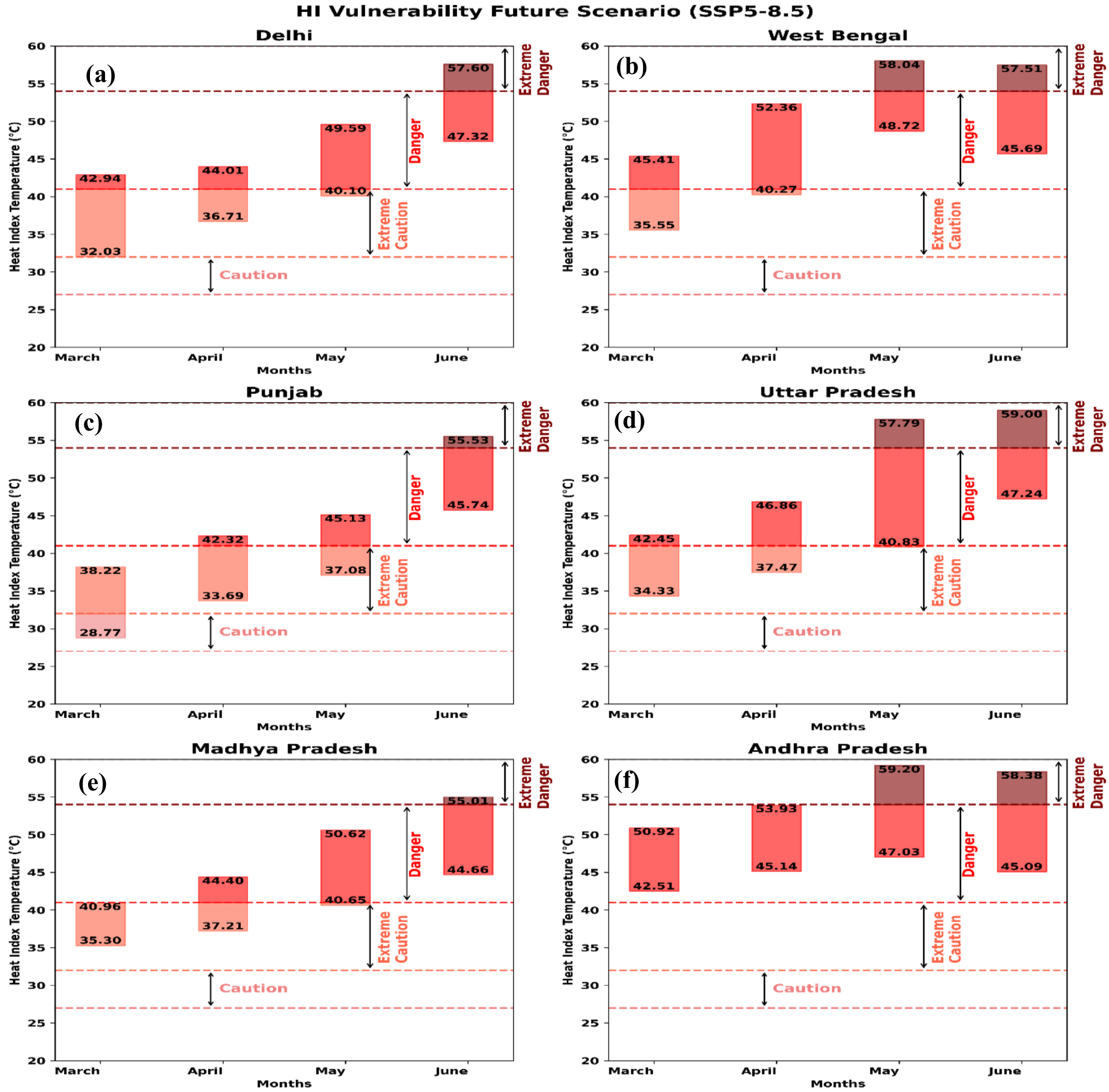

Figure 19. Future SSP5-8.5 Scenario HI Vulnerability of the Summer Months for (**a**) Delhi, (**b**) West Bengal, (**c**) Punjab, (**d**) Uttar Pradesh, (**e**) Madhya Pradesh, and (**f**) Andhra Pradesh.

The average HI for the Delhi region for March, April, May, and June has been depicted in **Figure 17a**, showing the average heat index temperature for the present scenario (2001–2024) along with future climate projection scenarios (2025–2049) of SSP2-4.5 and SSP5-8.5 in **Figure 18a** and **Figure 19a**, respectively. During March, Delhi is under both caution and no caution state spatially, but in April the average heat index ranges between 36.43 °C and 40.79 °C which is extreme caution to danger state. In May and June, HI is even higher than in April ranging from 41.18 °C – 55.19 °C and 46.53 °C – 56.36 °C, respectively, which is the danger to extreme danger state (**Figure 17a**). For the SSP2-4.5 scenario, Delhi experiences no caution, extreme caution, danger, and extreme danger states for March, April, May and June, respectively (**Figure 18a**). However, for the SSP5-8.5 scenario, no caution, caution, danger, and extreme danger states are experienced in Delhi for March, April, May and June, respectively (**Figure 19a**). In contrast, June exhibits the higher average HI values approaching to higher extreme danger state for future scenarios for Delhi compared to present scenario. The average HI of the West Bengal region for the present scenario (**Figure 17b**) shows that March is under no Caution state, and April experiences the average heat index ranging between 37.16 °C to 46.70 °C which is Extreme Caution to Danger state. May and June experience even higher heat index temperatures ranging from 40.97 °C–56.35 °C and 40.28 °C–53.50 °C, which represent the Danger to Extreme Danger and Danger states, respectively. For future SSP scenarios (**Figures 18b** & **19b**), March and April are in Caution and Extreme Caution states, but during May and June exhibit higher average Heat index values approaching to Extreme Danger state.

The average HI temperature of Punjab for the present scenario shows no Caution state for March but April experiences the average heat index ranging between 35.75 °C – 47.90 °C which is an Extreme Caution to Danger state (**Figure 17c**). While in May and June, Punjab region experiences even higher heat index temperature ranging from 49.05 °C – 55.38 °C and 48.72 °C – 56.34 °C, which are the Extreme Caution to extreme Danger, and Danger to Extreme Danger states, respectively (**Figure 17c**). However, future projections under different SSP scenarios (**Figures 18c** & **19c**) indicate that March is under the Caution State, while April, May and June exhibit higher average Heat index values approaching Extreme Caution, Danger, and Extreme Danger state, respectively. The average HI of the Uttar Pradesh region for March, April, May, and June for the present scenario is presented in **Figure 17d**. March shows no Caution state, April records the average HI ranging between 37.05 °C – 47.92 °C which is Extreme Caution to Danger state; May and June experience even higher heat index temperatures ranging from 42.18 °C – 55.05 °C and 45.10 °C – 56.89 °C, respectively, which is Danger to Extreme Danger state (**Figure 17d**). The future projection under different SSP scenarios (**Figures 18d** & **19d**) shows Caution State during March, with April, May and June exhibiting the higher average HI values approaching Extreme Caution, Danger, and Extreme Danger states, respectively (**Figures 18d** & **19d**).

Madhya Pradesh region shows no Caution state during March and extreme Caution to Danger states during April when the average HI values are in the range of 37.21 °C–44.18 °C in the present scenario (**Figure 17e**). However, during May and June, Madhya Pradesh region experiences Danger state as HI values are in the ranges of 40.70 °C–49.18 °C and 43.10 °C–50.17 °C (**Figure 17e**). During the projections under different SSP scenarios, Caution state is observed during March. In contrast, April, May, and June exhibit higher average HI values approaching Extreme Caution, Danger, and Extreme Danger states, respectively (**Figures 18e** & **19e**). The average HI for the Andhra Pradesh region shows Extreme Caution to Danger states for March and April in the present scenario, but the months of May and June experience even higher HI values which represent Danger to Extreme Danger state (**Figure 17f**). The future projections under SSP scenarios show Caution state during March, but April, May and June months exhibit higher average HI values approaching Extreme Caution, Danger, and Extreme Danger state, respectively (**Figures 18f** & **19f**).

It is seen that in the present scenario in Delhi for March and April, there is a threat to the human body due to Extreme Caution to Danger states, which may cause fatigue with prolonged exposure and activity, and could result in heat cramps if outdoor activity continues. In contrast, for May and June, the Danger to extreme Danger states are observed in which heat cramps and heat exhaustion are likely, and even death due to heat strokes is possible with continued exposure to heatwaves (**Figure 17**). Similar observations are also observed for the states of Punjab, Uttar Pradesh, and Andhra Pradesh. For Madhya Pradesh and West Bengal, similar vulnerability due to heat stress is observed except for West Bengal in the Month of May when Extreme Danger state is seen for which death due to heat strokes is possible if continued exposure to heatwaves occurs (**Figure 17**). For the SSP2-4.5 scenario, the vulnerability related to heat stress is similar for Madhya Pradesh and Uttar Pradesh for all months, but for Delhi, West Bengal, Punjab are different for the months of March and April (**Figure 18**), when compared to the present scenario (**Figure 17**). During the Months of June, the states of Delhi, Punjab, West Bengal reached Extreme Danger state and even the death due to heat strokes is possible if continued exposure to heatwaves occurs (**Figure 18**) compared to present scenario (**Figure 17**). Similar HI vulnerability is observed for SSP5-8.5 scenario except for Andhra Pradesh for which intense Extreme Danger state is seen for the months of May and June (**Figure 19**) for which heat strokes are possible for continued exposure compared to SSP2-4.5 scenario.

4. Conclusions

The analysis of heat index and related health problems has been analysed for the six states of India for the summer month using the available datasets for present and future climate change scenarios. We have also analysed the heatwave characteristics (frequency, duration, and intensity) to understand the vulnerability for the present and future scenarios related to heatwave and heat stress. The frequency of heatwaves is expected to rise in the future, making it crucial to identify heat risk zones at the national level and evaluate them using suitable indices for the development of early warning systems and mitigation strategies [70]. Our analysis shows that during March and April, Delhi experienced Extreme Caution to Danger condition of HI vulnerability for which fatigue is possible during prolonged exposure. Danger to Extreme Danger conditions of HI vulnerability are possible in May and June, which may lead to heat cramps and heat exhaustion, and continued exposure to heatwaves can cause heatstroke-related deaths. Similar observations are also observed for the states of Punjab, Uttar Pradesh, and Andhra Pradesh. However, for the states of Madhya Pradesh and West Bengal, vulnerability due to heat stress is observed as seen in Punjab, Uttar Pradesh, and Andhra Pradesh. For May, West Bengal has prevailed in the condition of Extreme Danger which may result in death due to heat strokes.

The vulnerability related to heat stress for Madhya Pradesh and Uttar Pradesh during the summer months is similar to the SSP2-4.5 scenario. However, Delhi, West Bengal, and Punjab are like the present scenario for March and April. SSP2-4.5 scenario also showed that Delhi, Punjab, and West Bengal reached an Extreme Danger state for which death due to heat strokes is possible if continued exposure to heatwaves occurs during June. The HI related vulnerability is similar to the SSP5-8.5 scenario except for Andhra Pradesh which shows an intense Extreme Danger state in May and June during which heat strokes are possible if continued exposure to heatwaves occurs compared to SSP2-4.5.

Death due to heat strokes is highly possible in the future in May and June for West Bengal, Uttar Pradesh, and Andhra Pradesh but in June for Delhi, Punjab, and Madhya Pradesh as seen from our analysis. Although the datasets used in this study are coarse, the key findings of this study provided a base of spatial variability of heat stress-related vulnerability for the six different states of India. At present, there seems to be a lack of resources for heat health preparedness in South Asia, and only a small number of early warning systems have been established [71]. Addressing heat stress would mitigate its impact on sustainability. Enhancing the liveability and functionality of cities has been discussed in previous studies [72,73]. Adopting the mitigation related to the heat strategies helps in improving the thermal comfort conditions. Implementation of heat mitigation strategies creates an opportunity for policymakers of governmental agencies, and geographers will help to develop sustainable cities [74].

Indeed, several cities and countries around the world have adopted heatwave preparedness plans [75]. In regions like India where the population is large with varying climatic conditions, the need for a wider preparedness strategy related to heat stress is extremely crucial. Thus, our analysis will help to take necessary precautionary measures for the local government agencies from heat stress-related vulnerability in the future.

Author Contributions

Conceptualisation, S.S. and A.C.; methodology, S.S., A.K. and V.S.; software, S.S.; validation, S.S., A.K. and V.S.; formal analysis, S.S., A.K. and V.S.; investigation, S.S., A.K. and V.S.; resources, S.S.; data curation, S.S.; writing—original draft preparation, S.S. and A.C.; writing—review and editing, A.C.; visualisation, S.S. and A.K.; supervision, A.C.; project administration, A.C.; funding acquisition, not applicable. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Data are freely available from the website cited in the data section. The code to produce the figures will be provided upon request.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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