Extreme temperature and rainfall event trends in the Middle Gangetic Plains from 1980 to 2018

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Regional-level studies aimed at identifying and assessing various types of extreme weather events and comprehending their effects on various sectors are crucial. In the present study, we have utilized the RClimDex software to compute the trend in temperature and precipitation extreme events in the Varanasi district of Uttar Pradesh, India, from 1980 to 2018. We employed both Mann–Kendall test and linear regression to test the statistical significance of the computed trend. Out of 13 temperature indices, 8 showed a significant trend while the remaining showed a non-significant trend. The annual mean maximum temperature, warm days, diurnal temperature range and a monthly minimum of maximum temperature had decreased significantly by 0.029ºC, 0.159 days, 0.032ºC and 0.122ºC/yr respectively, whereas cool days and cold spell duration had increased significantly by 0.264ºC and 0.372 days/yr respectively, indicating an increased cooling effect over the study area. Similarly, out of the 11 rainfall indices, only two showed a significant trend, while the remaining showed a non-significant trend. The increasing drought over the study area is evident as the number of rainy days and consecutive wet days have decreased significantly by 0.262 days and 0.058 days/yr respectively, with a non-significant increase in consecutive dry days during the same period. The weak negative non-significant trend of a maximum of five consecutive days of rainfall, very heavy rainfall days and total annual precipitation indicate the decreasing trend of floods. This study stresses the development of adaptation plans to overcome the adverse consequences of extreme weather events in Varanasi district.

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EVALUATING the consequences of climate change on local and regional levels as well as the accompanying extreme climate events is crucial for planning and developing effective adaptation practices. Extreme climate events will become more intense, last longer and occur more frequently due to climate change[1]. Extreme weather events are common in all climatic regions, and their incidence on a regular basis will cause havoc on the ecology as well as the socio-economic sectors of a region, including water, health, transportation and agriculture[2–4].

Climate change has caused a substantial alteration in the severity, recurrence and length of extreme weather events in many regions[5]. In recent years, information on the occurrence of extreme weather events has become increasingly vital for successful disaster management[6]. As a result, research focused on changing extreme weather events is progressively gaining importance as one of the most popular subjects in the field of climate change. Many studies have already been undertaken in India on time-series analysis of extreme rainfall and temperature events[4,7–11], which are found to vary across regions[12]. These studies, however, did not use adequate or recognized indices for comparison. Moreover, no such study is available for Varanasi, Uttar Pradesh, India. Under the World Meteorological Organization (WMO), the Expert Team on Climatic Change Detection and Indices (ETCCDI) has formulated a standardized collection of indices for climate extremes, enabling contrasts to be drawn

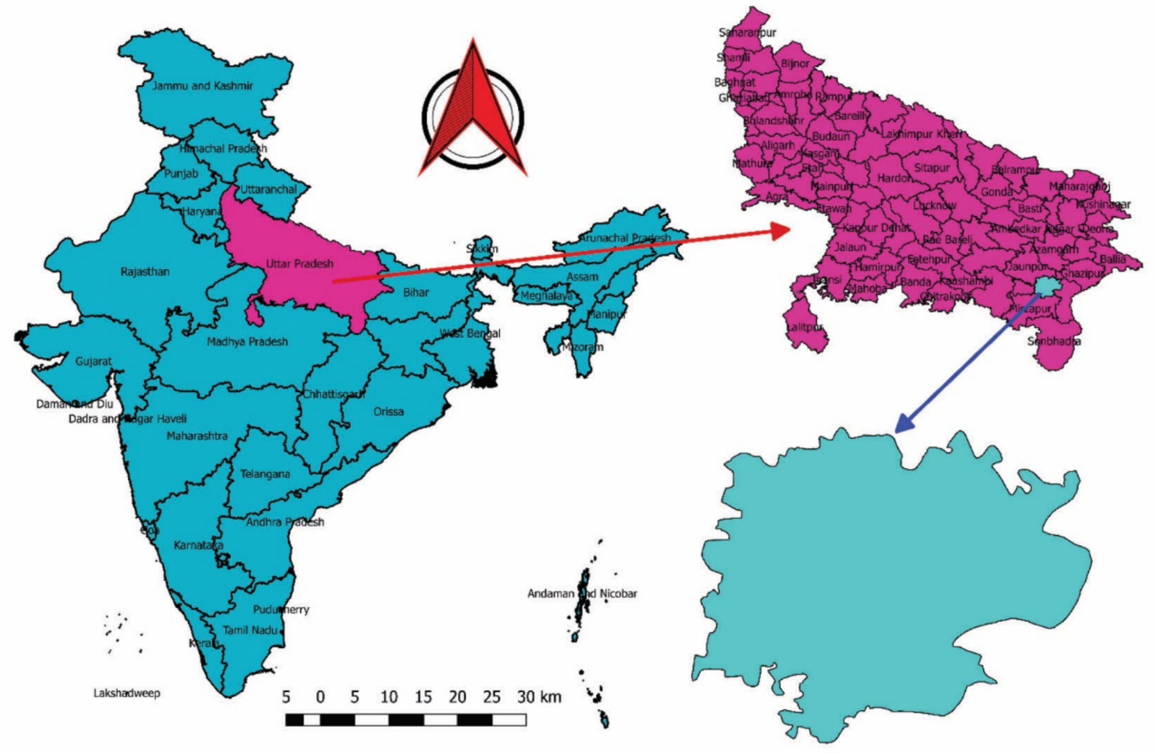

Figure 1. Map showing the study area.

between various regions around the world. These indices are globally recognized. Given the significance of extreme weather events, the present study utilized the ETCCDI indices to examine occurrences of extreme weather related to temperature and rainfall in Varanasi spanning from 1980 to 2018.

Materials and methods

Study area

Varanasi lies in the Middle-Ganges valley (left bank) in the southeastern region of Uttar Pradesh, at a lat. 25°19′08″N and long. 83°00′46″E, with an elevation of 80.71 m amsl (Figure 1). It is a cultural centre in North India that has long been linked to the Ganges River. Varanasi experiences a humid subtropical climate characterized by substantial temperature variations between winter and summer. The summer season, which commences in April and extends until June, is dry and accompanied by scorching hot gusts of wind referred to as ‘loo’. This is followed by the monsoon season, which spans from July to October. In winter (December to February), due to cold waves from the Himalayan region, the temperature of the city drops below 5°C; fog is common and there is diurnal temperature variation, with warm days and chilly nights. The yearly rainfall averages 1110 mm. The terrain is extremely fertile due to the Ganges’ low-level floods, which restore the topsoil on a regular basis.

Weather data

The extreme weather events associated with temperature and rainfall were studied using 39 years of daily data (1980–2018) recorded at the Agrometeorological Observatory of the Institute of Agricultural Sciences, Banaras Hindu University (BHU), Varanasi. Three weather parameters, namely maximum and minimum temperatures, and rainfall were used in this study. The invalid entries, such as negative rainfall and maximum temperature being less than or equal to minimum temperature were eliminated through a quality check to ensure the accuracy of the data. Additionally, the removal of outliers was carried out based on the threshold values of ±3 in the form of a standard deviation. Temperature outliers were identified by implementing the three-sigma level. India Meteorological Department (IMD), Pune, defines a rainy day as one with rainfall of 2.5 mm or more, a heavy rainfall day as one with rainfall of 64.5 mm or more, and a very heavy rainfall day as one with rainfall of 124.5 mm or more. Therefore, this study analysed trends in the occurrences of rainy days (R2.5), heavy rainfall days (R64.5) and very heavy rainfall days (R124.5).

Extreme weather event analysis

In this study, 13 temperature and 11 rainfall-related extreme weather indices were analysed for their trend using RClimDex package in R platform (Table 1). The complete

Table 1. Temperature and rainfall indices used in this study

	Unit
Temperature indices	
Annual mean maximum temperature (mean T_{max})	°C
Annual mean minimum temperature (mean T_{min})	°C
Cool nights (TN10p): Percentage of days when TN < 10th percentile	Days
Warm nights (TN90p): Percentage of days when TN > 90th percentile	Days
Warm days (TX90p): Percentage of days when TX > 90th percentile	Days
Cool days (TX10p): Percentage of days when TX < 10th percentile	Days
Warm spell duration indicator (WSDI): Annual count of days with at least six consecutive days when TX > 90th percentile	Days
Cold spell duration indicator (CSDI): Annual count of days with at least six consecutive days when TN < 10th percentile	Days
Diurnal temperature range (DTR): Monthly mean difference between TX and TN	°C
Max T_{max} (TXx): Monthly maximum value of daily maximum temperature	°C
Min T_{max} (TXn): Monthly minimum value of daily maximum temperature	°C
Max T_{min} (TNx): Monthly maximum value of daily minimum temperature	°C
Min T_{min} (TNn): Monthly minimum value of daily minimum temperature	°C
Rainfall indices	
Rainy day (R2.5): Rainfall received in a day is ≥2.5 mm	Days
R10: Annual count of days when rainfall ≥10 mm	Days
R20: Annual count of days when rainfall ≥20 mm	Days
Heavy precipitation days (R64.5): Annual count of days when rainfall ≥64.5 mm	Days
Very heavy precipitation days (R124.5): Annual count of days when rainfall ≥124.5 mm	Days
Maximum one-day precipitation (RX1day) in a year	mm
Maximum consecutive five-day precipitation (RX5day) in a year	mm
Annual total wet-day precipitation (PRCPTOT)	Mm
Simple daily intensity index (SDII): Annual total precipitation divided by the number of wet days (rainfall ≥1 mm) in the year	mm/day
Consecutive dry days (CDD): Maximum number of consecutive days with rainfall <1 mm	Days
Consecutive wet days (CWD): Maximum number of consecutive days with rainfall ≥1 mm	Days

information regarding input file preparation, installation of R and running the program is available in the *RClimDex User Manual*[13].

Statistics

To test the statistical significance of the trends, we employed a simple linear regression method and the Mann–Kendall (MK) test, a non-parametric test, using the Trend Toolkit software. The slope coefficient derived from these tests represents the annual average rate of change in the variable of interest, such as temperature or rainfall. A positive slope coefficient indicates an increasing trend, while a negative one indicates the opposite. This study considered the observed trends statistically significant at the 90% (P = 0.1%), 95% (P = 0.05%) and 99% (P = 0.01%) significant levels.

Results

Temperature-related extreme weather indices and their trends

Out of 13 temperature-associated indices studied, 8 (mean T_{max}, TX90p, WSDI, DTR, TXx, TXn, TNx and TNn) showed a decreasing trend, while 5 (mean T_{min}, TN10p, TN90p, TX10p and CSDI) showed an increasing trend (Figure 2). All of these extreme temperature indices are shifting in trend, indicating that the climate change process has begun and extreme temperature events are becoming more common in the area during the study period. The statistically significant drop in mean maximum temperature in Varanasi is evidence of regional-level climate change. During the study period, the annual mean maximum temperature (mean T_{max}) showed a statistically significant (at 0.05%) decreasing trend of –0.029°C/yr. The annual mean minimum temperature (mean T_{min}) showed a non-significant increasing trend (0.003°C/yr). Similarly, cool nights (TN10p) and warm nights (TN90p) showed a non-significant increasing trend at the rate of 0.156 and 0.121 days/yr respectively (Table 2). While the cool days (TX10p) increased significantly (at 0.01%) at the rate of 0.264 days/yr, warm days (TX90p) decreased significantly (at 0.05%) at the rate of –0.159 days/yr (Table 2).

Similarly, while the warm spell duration indicator (WSDI) decreased at the rate of –0.157 days/yr, although non-significantly, the cold spell duration indicator (CSDI) increased significantly (at 0.1%) at the rate of 0.372 days/yr. The diurnal temperature range (DTR) decreased significantly (at 0.01%) at a rate of –0.032°C/yr (Table 2). The monthly maximum value of daily maximum temperature (TXx) showed a non-significant decreasing trend (–0.006°C/yr), whereas the monthly minimum value of daily maximum temperature (TXn) showed a significant (at 0.01%) decreasing trend (–0.122°C/yr). Similarly, the monthly maximum value of daily minimum temperature (TNx) showed a non-significant decreasing trend (–0.011°C/yr), whereas the monthly minimum value of daily minimum temperature

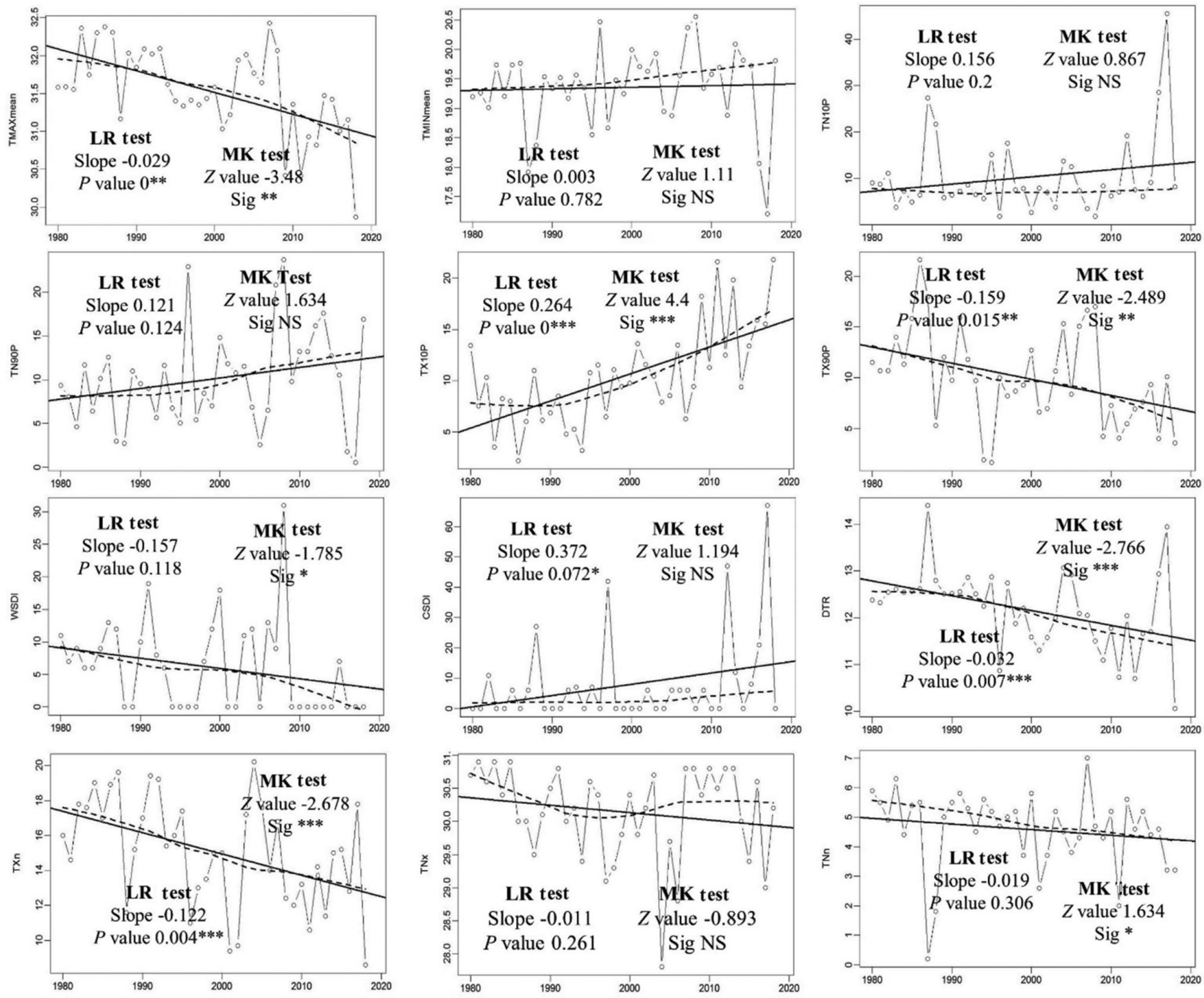

Figure 2. Trend graph of temperature-related indices.

(TNn) showed a significant (at 0.1%) decreasing trend (–0.019°C/yr) (Table 2).

Rainfall-related extreme weather indices and their trends

Out of 11 rainfall-associated indices studied, eight (R2.5, R10, R20, R124.5, RX1day, RX5day, PRCPTOT and CWD) showed decreasing trend and three (R64.5, SDII and CDD) showed an increasing trend (Figure 3). However, only three indices, viz. number of days in a year with rainfall of 2.5 mm, 10 mm and consecutive wet days (CWD) showed a significantly decreasing trend of –0.262, –0.146 and –0.058 days/yr respectively (Table 2). This is strong evidence that climate change is taking place over the Varanasi region. The number of heavy rainfall days (R64.5), simple daily intensity index (SDII) and consecutive dry days (CDD) showed a non-significant increase of 0.001 days, 0.043 mm/day and 0.533 days respectively (Table 2). On the other hand, the annual count of days when rainfall ≥10 mm (R10), ≥20 mm (R20), very heavy precipitation days (R124.5), maximum one-day precipitation (RX1day), maximum consecutive five-day precipitation (RX5day) and annual total precipitation (PRCPTOT) showed a non-significant decreasing trend of –0.146 days, –0.019 days, –0.005 days, –0.008 mm, –0.821 mm and –2.06 mm respectively (Table 2).

Discussion

Extreme weather events have a profound impact on agriculture, causing total crop failure, reduced yields, post-harvest losses and disruptions in the food supply chain. These effects are pronounced throughout the entire production and distribution process, from the farm to the marketplace where consumers purchase their goods[1]. Among them, rainfall and temperature are the two important parameters that have

Table 2. Trend and statistical significance of climatic indices by linear regression and MK test

Test	Linear regression		MK test	
Indices	Slope	Sig. level	*Z* value	Sig. level
mean T_{max}	–0.029	0.000**	–3.482	**
mean T_{min}	0.003	0.782	1.106	NS
TN10p	0.156	0.200	0.867	NS
TN90p	0.121	0.124	1.634	NS
TX10p	0.264	0.000***	4.400	***
TX90p	–0.159	0.015**	–2.489	**
WSDI	–0.157	0.118	–1.785	*
CSDI	0.372	0.072*	1.194	NS
DTR	–0.032	0.007***	–2.766	***
TXx	–0.006	0.702	–0.453	NS
TXn	–0.122	0.004***	–2.678	***
TNx	–0.011	0.261	–0.893	NS
TNn	–0.019	0.306	1.634	*
R2.5	–0.262	0.013**	–2.338	**
R10	–0.146	0.070	–1.766	*
R20	–0.019	0.738	–0.508	NS
R64.5	0.001	0.964	–0.930	NS
R124.5	–0.005	0.566	–0.126	NS
RX1day	–0.008	0.991	–0.377	NS
RX5day	–0.821	0.370	–1.094	NS
PRCPTOT	–2.060	0.484	–0.704	NS
SDII	0.043	0.251	1.408	NS
CDD	0.533	0.171	0.666	NS
CWD	–0.058	0.132*	–1.798	*

NS, Non-significant; *Significant at 0.1% level; **Significant at 0.05% level; ***Significant at 0.01% level.

a huge impact on agricultural production[11]. The rising frequency and simultaneous occurrence of multiple extreme weather events are expected to present a significant challenge to the agriculture sector, with particular implications for the livelihoods of small and marginal farmers. Changes in precipitation and temperature patterns are expected to have a profound impact on ecosystems, affecting both individual species and entire ecosystems. The effects of these alterations may be felt at all levels, from individual species to the broader ecosystem as a whole[14]. The changes in rainfall patterns may have a greater impact on agricultural production compared to temperature rises, particularly in the semiarid tropics, where crops frequently experience drought stress. This is because a lack of rainfall can significantly affect crop growth and yield, leading to reduced agricultural productivity and potential crop failure[15].

Impact of extreme temperature events on agriculture and its management

The study revealed that the extreme temperature indices are shifting in trend, indicating that extreme temperature events are becoming more common in Varanasi. Based on the analysis of monthly mean temperature data, a similar result of a significant decrease in mean maximum temperature in Varanasi has been reported[16]. The region is undergoing a process of cooling, which will extend the growth period of crops, thereby influencing crop productivity. A higher number of cold wave days in Varanasi during the post-monsoon season is reported based on the analysis of daily minimum temperature from 1971 to 2010 (ref. 17). Additionally, the notable shift in temperature has the potential to impact the outbreak of new crop diseases. This is because the reproduction, mortality, dispersion, migration patterns and population dynamics of insect pests, diseases and their natural predators are directly influenced by temperature[18]. Hence, the insect population may increase in Varanasi as a result of decreasing daytime temperature. As temperatures continue to rise in tropical regions, insects are expected to have a lower growth rate. This is because the current temperature level is already close to the optimal range for insect development and growth. In contrast, insects in temperate zones are likely to experience an increase in their growth rate, as well as early maturation and a greater number of generations[19]. The difference between maximum and minimum temperatures is narrowing, which in turn leads to a decreasing DTR. The changing temperatures are expected to have a significant impact on the length of the growing season[20]. Increasing CSDI and decreasing WSDI indirectly hint at the shortening of summer and extension of the winter season. This will have the advantage of lengthening crop growing period in *kharif* crops (mostly rice) and escaping forced maturity or terminal heat stress

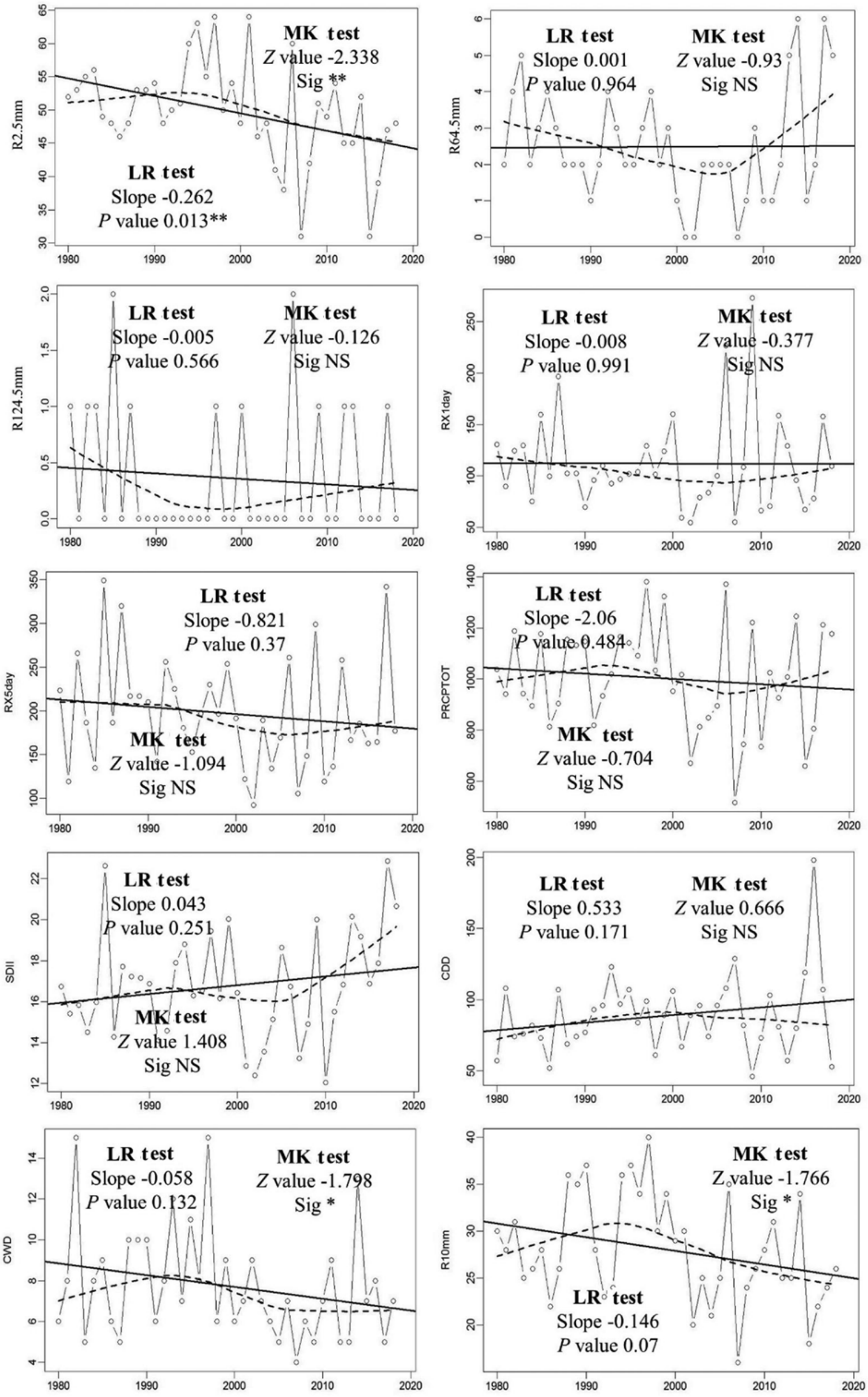

Figure 3. Trend graph of rainfall-related indices.

in *rabi* crops (mostly wheat). The significant decrease in the mean maximum temperature will extend the length of the growing season of crops, as high temperature shorten the length of the growing season[21,22]. The extended length of the growing season may lead to an increase in crop yield, and low temperatures will reduce photo-respiration in C3 crops (e.g. rice and wheat). However, the advancing winter season may lead to poor germination in *rabi* crops as the temperature reaches below optimum. Increasing cool days and decreasing warm days will have a beneficial impact on agricultural production by decreasing the moisture stress due to respiration in the crops.

Impact of extreme precipitation events on agriculture and its management

The distribution of rainfall in Varanasi changed significantly due to changes in R2.5 and CWD, and it is likely to present a significant challenge to the agriculture sector. Uneven distribution and decreasing annual rainfall in Varanasi have also been reported[23]. CWD and CDD are indicators used to monitor extreme precipitation and seasonal droughts. While CWD helps track prolonged periods of heavy rainfall, CDD is a useful indicator for detecting short-term droughts[24]. The increase in CDD is likely to cause the wilting of plants and the proliferation of insects, weeds and diseases, which will lead to higher production costs and crop failure[25]. The significantly decreasing CWD and non-significant increase in CDD reveal an increased risk of drought during the rainy season. This observation is supported by decreasing total annual precipitation and is in line with the finding of Pandey *et al.*[26]. A significant increase in the frequency of dry days in Varanasi has been reported[27]. The increasing R64.5 and SDII reveal the increasing intensity of rainfall and the chances of floods. The significant decrease in the number of rainy days, and the increasing R64.5 and SDII further increase the chances of drought/dry spells during the rainy season. The significant declining trends in the extreme precipitation indices (R2.5 and CWD) could be an influencing factor in the frequent occurrence of drought in the study area. A similar result of decreasing rainy days over Varanasi has also been reported[27]. Photosynthesis in plants is directly controlled by moisture availability and carbon dioxide concentration. The increasing drought will decrease crop yield by lowering plant photosynthesis and making the crop more susceptible to biotic and abiotic stresses. A similar result of increased heavy rainfall events, and decreased low and medium rainfall events over India has been reported[28]. The poor distribution of rainfall will have a negative effect on agricultural production. The chance of droughts and floods occurring has increased over the years. The increasing frequency of wet days and extreme wet days could lead to nutrient leaching, topsoil erosion, waterlogging, and pest and disease outbreaks, resulting in low crop yield and food supply chain disruptions[29].

Heavy rainfall events such as floods pose a threat to the survival of insects and can disrupt their diapause by flooding crop fields. Additionally, insect eggs and larvae are susceptible to being washed away by heavy rainfall and flooding[30]. Small-bodied pests such as aphids, mites, jassids, whiteflies, etc. are particularly vulnerable to being carried away by heavy rainfall[31]. The decreasing number of rainy days, total precipitation, heavy precipitation and consecutive rainfall amounts will favour the incidence and survival of these pests (mainly sucking pests). The decreasing frequency of very heavy rainfall and consecutive rainy days is likely to enhance nutrient use efficiency by reducing leaching loss and preventing topsoil erosion and waterlogging that would result in high crop yields. The decreasing day temperatures (T_{max}), warm days (TX90p), rainy days (R2.5), and very heavy precipitation (R64.5) along with increasing cold days, are also likely to result in the emergence of new pests, parasites and diseases, all of which will have a significant impact on agriculture[32].

Conclusion

The increasing cooling effect and changes in the precipitation distribution over Varanasi are evident from this study. Based on various extreme weather event trends, it is predicted that droughts will become more frequent in the coming years, while the frequency of flood events is expected to decrease. This is due to changes in the distribution of rainfall. Although the daily maximum temperature is decreasing, drought events are expected to be more frequent due to increasing consecutive dry days, decreasing consecutive wet days, and the annual count of rainy days. The temperature and precipitation shift is likely to bring a shift in insect pests, and the incidence of diseases and parasites in the agriculture sector. To mitigate the impacts of rising extreme temperatures and precipitation events on the agriculture sector, it is crucial to implement actionable adaptation options. This requires urgent planning and the development of strategies to counteract the threats posed by extreme weather events. The findings of this study can be useful for decision-makers to design effective mitigation and adaptation strategies aimed at minimizing the damage caused by extreme temperature and rainfall events in the Varanasi region. This study also helps enrich the references for a better understanding of regional-level climate change.

Conflict of interest: The authors declare that they have no potential conflict of interest.

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