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Temperature and precipitation are adversely affecting wheat yield in India

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ABSTRACT

An understanding of the climate-crop yield relationship has remained elusive. Wheat is one of the essential food crops globally. India is the second-largest wheat producer. Herein, we evaluate 50 years of detailed climate and wheat crop statistics (1966–2015) to spatially analyze temperature and precipitation trends and their impact on wheat yield across 29 Indian states using statistical methods. Temperature and precipitation are refined for seasonal (*Rabi* season), annual, and monthly durations at the state level because state is the administrative unit in India for adaptation strategies and mitigation purposes. We find that temperature has been increasing (statistically significantly) across all the Indian states, whereas precipitation change has been statistically non-significant. The seasonal temperature has harmed ~99.85% of India's wheat harvested area (i.e., ~24.1 million hectares, 21 Indian states). Seasonal precipitation has harmed ~56.26% of the wheat harvested area (i.e., ~13.6 million hectares, eight Indian states). February temperature and March precipitation demonstrate the most adverse impact on wheat yield. Climate variability explains up to ~78% wheat yield variability across Indian states. These results help identify the effects of changing climate on wheat yield and thus demand immediate attention and a response plan to develop adaptation strategies to address climate change.

Key words: climate change, India, precipitation trends, temperature trends, wheat yield

HIGHLIGHTS

- Temperature and precipitation trends are investigated using parametric and non-parametric methods.
- Results demonstrate statistically significant rise in *Rabi* season and annual temperatures across India.
- Twenty-one Indian states demonstrate negative correlation between *Rabi* temperature and wheat yield.
- Temperature and precipitation variables explain up to ~78% of wheat yield variability across Indian states.

1. INTRODUCTION

Various scholars have reported changes in climate parameters in different world regions (Banda *et al.* 2021; Jiao *et al.* 2021). Regional temperatures increased significantly in the 20th century (Jones *et al.* 2012). The temperature rise has been even more noticeable so far in the 21st century (IPCC 2014). The changes are visible in global and regional rainfall patterns as the Earth's rain belts are redistributing (Putnam & Broecker 2017). Consequently, the temperature and rainfall variability/trends are affecting crop yields (Lobell & Field 2007; Asseng *et al.* 2015). It has been suggested that the global wheat yields would reduce by 6% with an increase of each degree Celsius in global mean temperature (Zhao *et al.* 2017).

Climate variability directly influences agricultural production and yields (Mall *et al.* 2006; Birthal *et al.* 2014). The rise in temperature and changes in rainfall have adversely affected crop production (Alejo 2021). Temperature and precipitation trends for 1980–2008 had impacted crop yields globally (Lobell *et al.* 2011). Climate variability explained ~32–39% of the global crop yield variability (Ray *et al.* 2015). Governments and farmers can manage non-climate factors but find it difficult to change the impact of climate, particularly temperature and precipitation, on crop yields (Alemayehu & Bewket 2016). Agriculture is mainly dependent on climate (even more so in developing countries); therefore, the impact of climate change and variability on agricultural production and yields is generally significant (Eticha *et al.* 2021).

India accounts for ~13.6% of the world's wheat production and ~13.8% of the world's wheat harvested area (FAOSTAT 2018). Such large numbers station India at the second position in the world's wheat production and first position in the wheat harvested area (FAOSTAT 2018). India is projected to be the most populous country in the world by 2027, anticipated to have a 1.7 billion population by 2050 (United Nations Population Division 2019), therefore requiring more and more food to feed the people. There is a need to improve wheat and rice production by 2 million tons every year to maintain self-sufficiency (Bhalla *et al.* 1999). However, it was recently found that wheat yields are not improving in a large Indian area (Madhukar *et al.* 2020; Madhukar *et al.* 2021). The non-improvement in agricultural yields might have severe consequences for food supply and livelihoods (Tilman *et al.* 2002). Therefore, it becomes crucial to comprehensively understand and investigate temperature and precipitation trends and their effect on wheat yields across Indian states.

Many scholars have studied the climate trends (temperature and precipitation) at various sub-national scales in India. There have been two approaches to analyze spatio-temporal trends in climate and meteorological variables: parametric and non-parametric (Malik & Kumar 2020). The parametric approach includes regression analysis, whereas the Mann-Kendall, Sen's slope, and modified Mann-Kendall tests are the most widely used non-parametric trend detection tests (Meshram *et al.* 2017; Bisht *et al.* 2018).

For example, Arora *et al.* (2005) studied temperature trends in India using the non-parametric Mann Kendall test. The authors used the four weather seasons, i.e., winter, summer, monsoon, and post-monsoon, to investigate and report rising temperature trends for India. Patra *et al.* (2012) studied the rainfall trends in Orrisa, India, over 1871–2006. The authors used both parametric and non-parametric tests. Their results showed long-term not-significant downward trends in annual and monsoon rainfalls, but an upward trend in the post-monsoon season. Rainfalls during the summer and winter seasons demonstrated upward trends. Duhan & Pandey (2013) examined the temporal and spatial changes in precipitation across 45 districts of Madhya Pradesh, India, over 1901–2002 on an annual and seasonal basis, using Mann Kendall and Sen's slope tests. Jain *et al.* (2013) investigated the long-term trends of temperature and rainfall in northeast India for 1871–2008 using Mann Kendall and Sen's slope tests. The authors reported increasing trends for temperature and no clear significant trends for precipitation in the region.

Chakraborty *et al.* (2013) analyzed the rainfall trends and variability in the Seonath river basin, Chhattisgarh, India, using Mann Kendall, Sen's slope, modified Mann Kendall, and Spearman's Rho tests. The results suggested the decreasing trends in seasonal and annual rainfalls. Suryavanshi *et al.* (2014) studied the long-term historical changes in temperature and rainfall during annual, monsoon, winter, and summer seasons for Betwa basin, central India, using Mann Kendall and modified Mann Kendall tests. The results suggested upward trends for winter temperatures and downward trends for seasonal and annual precipitation. Pingale *et al.* (2014) employed Mann Kendall and Sen's slope tests to identify trends in temperature and rainfall during monsoon, non-monsoon, and annual seasons, for 33 urban centers of Rajasthan, India. The authors found significant changes in temperature and rainfall trends in most centers. Goyal (2014) investigated long-term rainfall trends during 1901–2002 over Assam, India. The author used the Mann-Kendall and Sen's slope tests for trend analysis and considered three weather seasons of winter, summer, and monsoon to compare variations.

Lacombe & McCartney (2014) studied the daily rainfall data for India (1951–2007), employing the Mann Kendall test. They reported downward rainfall trends across central India and upward rainfall trends over northeast and south. Subash & Sikka (2014) studied the temperature and rainfall data of India's 30 meteorological sub-divisions for 1904–2003, employing Mann Kendall and Sen's slope tests. They reported significant upward trends in India's annual maximum temperature and rainfall. Nair *et al.* (2014) studied the spatio-temporal trends in rainfall over Kerala, India, using the Mann Kendall test and reported decreasing trends in almost all regions of Kerala.

Applying Mann Kendall and Sen's slope tests on the Indian Institute of Tropical Meteorology (IITM) dataset for temperature and rainfall, Mondal *et al.* (2015) documented significant increasing trends for winter and post-monsoon temperatures over 1901–2007 and decreasing trends for annual and monsoon rainfall over 1871–2011 in India. Chandniha *et al.* (2017) investigated the temporal and spatial variability in annual, seasonal, and monthly precipitation for Jharkhand, India, using Mann Kendall, Sen's slope, and modified Mann Kendall tests. The results suggested decreasing annual, monsoon, and winter precipitation trends in Jharkhand during 1901–2011. Jain *et al.* (2017) investigated the trends in annual rainfall and peak flows for seven major river basins in India, employing Mann Kendall and Sen's slope tests. The results showed increasing trends in yearly peak rainfalls for most river basins. For the number of rainy days, two river basins (i.e., Cauvery and Brahmani and Baitarani) demonstrated rising trends, but the trends were downward for the remaining five river basins. Chandrakar *et al.* (2017) studied the long-term spatial and temporal trends in annual and seasonal (i.e., pre-monsoon/summer, monsoon, and post-monsoon/winter seasons) precipitation over Kharun watershed, Chhattisgarh, India, using Mann Kendall and Sen's slope tests. The results suggested a significant decrease in rainfall trends for annual and seasonal time series over 1901–2015.

Kumar *et al.* (2017) investigated the spatial patterns in rainfall trends for Gujarat, India. The authors employed satellite-based raster datasets and geographic information system (GIS) using Spearman Rank Order Correlation, Mann Kendall, and Kendall Rank Correlation tests. The comparative assessment of the three tests highlighted a fair alignment/agreement in the results of the three tests. However, the rainfall trends identified by the Mann Kendall and Kendall Rank Correlation tests were found to be more robust. Meshram *et al.* (2017) studied long-term trends and variability in annual, seasonal, and monthly precipitations for Chhattisgarh, India, using both parametric and non-parametric tests, such as Mann Kendall, Sen's slope, linear regression, and Spearman's Rho tests. The results suggested decreasing trends in annual and monsoon precipitations for most stations in Chhattisgarh. Ghosh (2018) investigated the spatial patterns of rainfall trends in West Bengal, India. The rainfall trends were studied at the annual and seasonal scales: monsoon, post-monsoon, winter, and summer. The authors used the non-parametric methods (i.e., Mann-Kendall and Sen's slope tests) to identify trends and their magnitudes over 1901–2002. The results revealed an overall increase in annual (2.61%), a substantial increase in post-monsoon (33.87%), a considerable decline in winter (14.83%) and summer (4.03%), and a minor rise in monsoonal rainfall (1.21%).

Ross *et al.* (2018) investigated changes in Indian temperature (during pre-monsoon, monsoon, and post-monsoon seasons) over the past seven decades. Comparing the decadal means for the 2000s with those of the 1950s, the authors reported a consistent temperature rise over north-western and southern India. Praveen *et al.* (2020) analyzed the long-term rainfall trends in India using non-parametrical approaches: the Mann-Kendall and Sen's innovative trend analysis methods. The authors used the rainfall data from 1901 to 2015 across India at the meteorological division level. Malik & Kumar (2020) examined the temporal and spatial trends in the rainfalls in Uttarakhand, India, employing parametric (i.e., linear regression analysis) and non-parametric (i.e., Man Kendall, Sen's slope, and modified Mann Kendall) tests. They reported significantly upward and downward rainfall trends in annual, seasonal, and monthly time series in 13 districts of Uttarakhand.

It is evident from the above literature review that most of the climate variability studies in India investigate climate trends based on either annual (January to December) or seasonal climate variables using the conventional classification of four weather seasons, i.e., Post-monsoon (October to November), Winter (December to February), Pre-monsoon (March to May), and Monsoon (June to September). In comparison, investigating climate trends per cropping season (i.e., *Rabi* and *Kharif*) will provide more practical insight into the impact of climate trends on crop yields. Understanding climate trends during the *Rabi* cropping season is critical as wheat (one of India's most vital food crops) is grown during the *Rabi* season. Therefore, the present manuscript analyzes the trends in temperature and precipitation during 1966–2015 at national, state, and selected district scales using wheat-growing *Rabi* cropping season in India. Both approaches are employed, i.e., parametric (linear regression analysis) and non-parametric (Mann Kendall, Sen's slope, and modified Mann Kendall tests). The uniqueness of the climate trend analysis presented in the manuscript lies in the use of cropping season over weather seasons; availability of results at three scales: national, state, and district; and employing multiple trend analysis methods, i.e., simple linear regression, Mann Kendall, Sen's slope, and modified Mann Kendall tests, together.

Further, we also analyzed 50 years' (1966–2015) climate and wheat yield data to understand how wheat yields are affected by changing temperature and precipitation across Indian states. A quantitative and spatial perspective on climate-yield relationships across India will enable Indian states to evolve and execute appropriate adaptation strategies. The spatial understanding of the statistical relationships between climate variability and wheat yields in India is of paramount importance because wheat is one of India's most important food crops – both in production and area under cultivation. Against this backdrop, the current research paper aims to spatially present temperature and precipitation variability trends in India, and investigate the relationship of the temperature and precipitation variability with wheat yield variability across Indian states by employing statistical methods.

2. MATERIALS AND METHODS

2.1. Climate data

Climate data (1966–2015) was obtained from the Climate Research Unit (CRU), University of East Anglia, UK (http://www.cru.uea.ac.uk/) for India and 29 Indian states. CRU provides high-resolution monthly climate data on a 0.5° latitude by 0.5° longitude grid covering all land surfaces (Harris *et al.* 2020). Climate data is derived by interpolating climate anomalies from the extensive weather station observations using angular distance weighting (ADW). Moreover, CRU climate data has been used in various climate impact studies (Duncan *et al.* 2016). We investigated two climate variables in this study: mean temperature and total precipitation. Both the climate variables were refined to the following three levels – seasonal, annual, and monthly:

- Wheat is grown during the *Rabi* season in India. *Rabi* season starts from October–November and ends in March–April. So, we estimated the seasonal climate variables (mean temperature and total precipitation) corresponding to the October–April period (*Rabi* season).
- To identify the impact of annual climate on wheat yield in India, we estimated the annual climate variables (mean temperature and total precipitation) corresponding to the May–April period. We chose the annual period from May to April because the *Rabi* season ends in April. It helped understand the impact of antecedent and average conditions of the prior 12 months (May to April) on wheat yield.
- We estimated monthly climate variables (mean temperature and total precipitation) during the *Rabi* season (October to April) to identify critical months when the climate is affecting wheat yield.

2.2. Climate trend analysis

We employed parametric method (i.e., simple linear regression) and non-parametric methods (i.e., Mann Kendall, modified Mann Kendall, and Sen's slope tests) for trend analysis of climate variables.

2.2.1. Simple linear regression

Simple linear regression is the most commonly used method to identify trends in time series data. We fitted the climate variables (temperature and precipitation, seasonal and annual) into the following simple linear regression models to identify the temperature and precipitation trends over 1966–2015 for India and 29 Indian states:

$$\textit{seasonal temperature} = \alpha_1 + (\beta_1 \times \textit{year}) + \varepsilon_1 \tag{1}$$

$$\textit{annual temperature} = \alpha_2 + (\beta_2 \times \textit{year}) + \varepsilon_2 \tag{2}$$

$$\textit{seasonal precipitation} = \alpha_3 + (\beta_3 \times \textit{year}) + \varepsilon_3 \tag{3}$$

$$\textit{annual precipitation} = \alpha_4 + (\beta_4 \times \textit{year}) + \varepsilon_4 \tag{4}$$

Here, α, β, and ε are intercepts, regression coefficients, and error terms. Regression coefficients give the nature and magnitude of trend in the respective climate variable. We used state-wise trends because a state is the most important administrative unit under the federal structure of India.

2.2.2. Mann Kendall, modified Mann Kendall, and Sen's slope tests

We also analyzed the trends in the above climate variables applying the Mann Kendall test (Mann 1945; Kendall 1975). The Mann Kendall test was computed using the following equations:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \tag{5}$$

here n is the number of observations in the time series, x_i is the ith observations rank (i=1, 2…n–1), and x_j is the jth observations rank (j=i+1, 2…n). The sign function was calculated as follows:

$$sgn\,(x_j - x_i) = \begin{cases} 1; & if\ (x_j - x_i) > 0 \\ 0; & if\ (x_j - x_i) = 0 \\ -1; & if\ (x_j - x_i) < 0 \end{cases} \tag{6}$$

The Mann Kendall test statistics S for a normally distributed time series having sample size $n>10$ with mean $E(S)$ and variance $Var(S)$ were as follows:

$$E(S) = 0 \tag{7}$$

$$Var(S) = \frac{n(n-1)(2n+5)}{18} \tag{8}$$

The Mann Kendall test Z statistics were calculated as follows:

$$Z\ statistics = \begin{cases} \dfrac{S-1}{\sqrt{Var(S)}};\ if\ S > 0 \\ 0;\ if\ S = 0 \\ \dfrac{S+1}{\sqrt{Var(S)}};\ if\ S < 0 \end{cases} \tag{9}$$

The Mann Kendall test has a low sensitivity to outliers and does not need a normally distributed dataset; however, the time series must be independent of serial correlation. For a serially correlated time series, we employed a modified Mann Kendall test using the Yue *et al.* (2002) trend-free pre-whitening (TFPW) method. We calculated the lag-1 serial correlation coefficient for all the time series and applied the modified Mann Kendall test when the lag-1 serial correlation coefficient was statistically significant at 5% confidence limits. Modified Mann Kendall test was not employed to detect the trend for non-significant serially correlated time series. The positive and negative values of Z statistics of Mann Kendall and modified Mann Kendall tests indicated increasing and decreasing trends, respectively.

Sen's slope test was used to determine the magnitude of the trend (Theil 1950; Sen 1968). The Sen's slope was computed as follows:

$$(Sen's\ Slope)_{ij} = median\left(\frac{x_j - x_i}{j-i}\right)\ i<j \tag{10}$$

$$(Sen's\ Slope)_{median} = (Sen's\ Slope)_{\frac{N+1}{2}},\quad if\ N\ is\ odd \tag{11}$$

$$(Sen's\ Slope)_{median} = \frac{1}{2}\left[(Sen's\ Slope)_{\frac{N}{2}} + (Sen's\ Slope)_{\frac{N+1}{2}}\right],\quad if\ N\ is\ even \tag{12}$$

The positive value of Sen's slope showed an increasing trend, and a negative value of Sen's slope demonstrated a decreasing trend.

In addition to trend analysis of state-level CRU data, we also investigated temperature and precipitation trends in selected Indian districts using simple linear regression, Mann Kendall, modified Mann Kendall, and Sen's slope tests. For this, we identified two districts from each of eight major wheat-producing Indian states (i.e., districts having minimum and maximum seasonal mean temperature in that state). Similarly, we identified two more districts from each of eight major wheat-producing Indian states (i.e., districts having minimum and maximum seasonal total precipitation in that state). Eight major wheat-producing states considered in this analysis were: Uttar Pradesh, Punjab, Haryana, Madhya Pradesh, Bihar, Gujarat, Rajasthan, and Maharashtra.

2.3. Wheat data

Annual wheat yields for all the 29 Indian states during 1966–2015 were obtained from the Ministry of Agriculture and Farmers' Welfare, Government of India. The 23 Indian states (excluding Goa, Kerala, Manipur, Mizoram, and Tamil Nadu) produced ~99.8% of the total wheat production in India during 1966–2015. During the study period, the wheat production was either negligible or inconsistent in the remaining five Indian states (Goa, Kerala, Manipur, Mizoram, and Tamil Nadu). So, the wheat yield analysis was performed for the 23 Indian states contributing to ~99.8% of total wheat production in India.

In 2014, the Indian state of Andhra Pradesh was bifurcated into two states: (1) Andhra Pradesh (kept the name of mother state) and (2) Telangana. Throughout this paper, Andhra Pradesh* (i.e., with an asterisk) means the joint state of Telangana and Andhra Pradesh; and Andhra Pradesh (i.e., without the asterisk) means the newly formed state in 2014.

Similarly, the Indian states of Chhattisgarh and Madhya Pradesh were formed in 2001 by bifurcating Madhya Pradesh. The wheat data for these newly formed states was available only from 2001, and the wheat data for the joint state of Madhya Pradesh was available before 2001. We computed the average annual production over 2001–2016 for the new states of Chhattisgarh and Madhya Pradesh and estimated the ratio between the two. We applied this ratio on the pre-2001 annual wheat production time series of joint state to extrapolate annual productions for new states before 2001. Likewise, the annual harvested areas before 2001 were computed for the new states of Chhattisgarh and Madhya Pradesh using the same logic. Consequently, annual wheat yields before 2001 for Chhattisgarh and Madhya Pradesh were computed from the annual wheat productions and annual wheat harvested areas for the period before 2001. The same procedure was followed for Uttarakhand/Uttar Pradesh and Jharkhand/Bihar.

We did not use the wheat data of the Indian state of Assam from 1966 to 1970 because Assam also incorporated the areas of Mizoram and Meghalaya during this time. So, the wheat yield data of Assam was used from 1971. Moreover, we also obtained and analyzed district-level wheat yield data for selected Indian districts from the Ministry of Agriculture and Farmers' Welfare, Government of India.

2.4. Detrending of wheat yields

The detrending method was used to eliminate the impact of non-climate factors on crop yields, such as technology and crop management. Several studies have applied linear and non-linear detrending models to remove the non-climatic impact from crop yields (Parthasarathy *et al.* 1992; Bapuji Rao *et al.* 2014). We selected the best-fit models for wheat yields across all Indian states (and selected Indian districts) for detrending. To do so, wheat yield data for all Indian states (and selected Indian districts) was fitted into four types of regression models:

1. An intercept-only model ($Y=a$),
2. A linear model ($Y=a+bt$),
3. A quadratic model ($Y=a+bt+ct^2$), and
4. A cubic model ($Y=a+bt+ct^2+dt^3$)

Here Y is the wheat yield and t is the year. Then, the best-fit models across Indian states (and selected Indian districts) were chosen based on the lowest value of the Akaike Information Criterion (AIC) developed by Akaike (1974). These best-fit models were used for detrending, and wheat yield residuals were calculated from observed and predicted yields. After detrending, wheat yield data was ready for correlation analysis with climate variables to evaluate climate-yield relationships.

2.5. Correlation analysis and climate-wheat yield relationships

Pearson's correlation analysis, followed by a significance test, is the method many scholars have used to assess the relationship between climate variables and crop yields (Nageswararao *et al.* 2018). The sign and magnitude of the correlation coefficient indicate the nature and the strength of the relationship, respectively. We performed correlation tests between climate variables (seasonal, annual, and monthly; temperature and precipitation) and detrended wheat yields to estimate Pearson's correlation coefficients across Indian states and selected Indian districts. All computations, including estimation of correlation coefficients, calculation of AIC, and significance tests, were performed using R v 3.5.1 (R Development Core Team 2018).

2.6. Detrending of climate variables

In order to fit climate variables into regression models, it is required to detrend the climate variables. We detrended the seasonal and annual climate variables by fitting them into the following linear functions:

$$T_d = T - T_l \tag{13}$$

$$P_d = P - P_l \tag{14}$$

Here, T and P are the obtained temperature and precipitation values from CRU. The T_d and P_d denote the detrended values, and T_l and P_l represent the linear fit values.

2.7. Regression models

After the linear detrending of climate variables, we performed multiple linear regressions with detrended yield (response variable) and detrended climate variables (explanatory variables). We fitted the wheat yields and climate variables for each Indian state in the four types of regression models, uniquely highlighting if wheat yield variability was explained by the variations in temperature, precipitation, both, or their interaction:

- Temperature only models ($Y=f$ (ST, AT)),
- Precipitation only models ($Y=f$ (SP, AP)),
- Temperature and precipitation models ($Y=f$ (ST, AT, SP, AP)), and
- Complex models ($Y=f$ (ST, AT, SP, AP, $ST\times SP$, $AT\times AP$))

Here Y is the annual yield, ST is seasonal temperature, AT is annual temperature, SP is seasonal precipitation, and AP is annual precipitation. Square terms of detrended climate variables (residuals) were included for a non-linear relationship between climate variables and wheat yields. We identified the best-fit models by calculating the Akaike Information Criterion (AIC) developed by Akaike (1974). The regression models with the lowest Akaike Information Criterion (AIC) were selected as the most appropriate models connecting yields and climate variables in Indian states. The best-fit models were further analyzed with a significance test at $p<0.1$ to determine whether the models were also statistically significant. Models having p values greater than 0.1 were identified as not significant. Further, we calculated the coefficients of determination (R^2) for the best-fit models. R^2 gives the percentage of yield variability explained by climate variability.

3. RESULTS AND DISCUSSION

3.1. Temperature trends

We determined the temporal variations in the temperature trends for India and each Indian state using simple linear regression models and Man Kendall/modified Mann Kendall tests. For simple linear regression models, the sign and value of the regression coefficients determine the nature of the trends and the magnitudes of the change, respectively. p values detect the significance levels in the trends. For Mann Kendall/modified Mann Kendall tests, the positive and negative values of Z-statistics indicate increasing and decreasing trends, respectively. The estimation of Theil Sen's slope provides the magnitude of the trend.

Figure 1(a) presents the temporal variation in mean seasonal temperature (*Rabi* season) for India from 1966 to 2015 using a simple linear regression model. It depicts that the seasonal temperature for India has increased substantially at 0.20 °C per decade since 1966. The increasing temperature trend is statistically significant at $p<0.01$ ($R^2=0.39$), ranging between 20.9 °C (in 1972) and 22.8 °C (in 2009), with a mean of 21.7 °C and a standard deviation of 0.5 °C during 1966–2015. The modified Mann Kendall test also demonstrates a statistically significant increase in seasonal temperature at the rate of

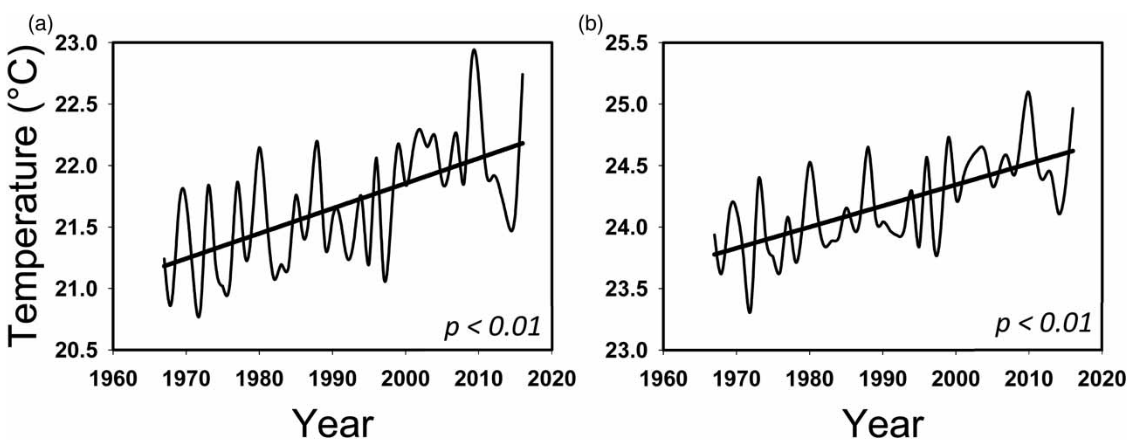

Figure 1 | Temporal variation in (a) seasonal temperature (*Rabi* season) and (b) annual temperature (May to April) for India from 1966 to 2015 using simple linear regression models.

0.21 °C per decade ($p<0.01$). We observed that mean seasonal temperature was 21.3 °C (during 1966–1975), 21.5 °C (during 1976–1985), 21.6 °C (during 1986–1995), 21.9 °C (during 1996–2005), and 22.1 °C (during 2006–2015) in India.

Similarly, the mean annual temperature for India depicts an increasing trend of 0.17 °C per decade for a simple linear regression model (Figure 1(b)). The temperature trend is statistically significant at $p<0.01$ ($R^2=0.46$). The modified Mann Kendall test demonstrates a statistically significant increase in annual temperature at the rate of 0.18 °C per decade ($p<0.01$). The minimum and maximum annual temperatures were 23.3 °C and 25.1 °C in 1972 and 2010 respectively, with a mean of 24.2 °C and a standard deviation of 0.4 °C during 1966–2015. We noted that mean annual temperature was 23.9 °C (1966–1975), 24.0 °C (1976–1985), 24.1 °C (1986–1995), 24.4 °C (1996–2005), and 24.6 °C (2006–2015) respectively in India. Overall, the above results show that the seasonal and annual temperatures have increased (statistically significantly) for India during 1966–2015.

To understand seasonal temperature trends (over 1966–2015) for different Indian states, we fitted the seasonal temperatures (*Rabi* season) in the simple linear regression models across Indian states (Supplementary Figure S1). We also applied Mann Kendall/modified Mann Kendall tests to detect state-level trends in seasonal temperatures. Table 1 summarizes the regression coefficients, Sen's slopes, and the significance levels for the respective Indian states.

We find that seasonal temperatures (*Rabi* season) for all Indian states have increased substantially since 1966. Twenty-seven Indian states (except Mizoram and Tripura) show warming trends in seasonal temperatures statistically significant at $p<0.01$. Mizoram and Tripura show warming trends in seasonal temperatures statistically significant at $p<0.05$. The magnitude of change in seasonal temperature is maximum in Jammu & Kashmir (0.277 °C per decade for simple linear regression, 0.280 °C per decade for modified Mann Kendall test) and minimum in Tripura (0.109 °C per decade for simple linear regression, 0.10 °C per decade for modified Mann Kendall test).

Similarly, we investigated the annual temperature (May-April) trends over 1966–2015 across Indian states by fitting linear regression models (Supplementary Figure S2). We also applied Mann Kendall/modified Mann Kendall tests to detect trends in annual temperatures (Table 1). The result shows that annual temperature exhibits increasing trends (statistically significant at $p<0.01$) in all the 29 Indian states. The magnitude of change in annual temperature is maximum in Sikkim (0.222 °C per decade) and minimum in Tripura (0.112 °C per decade) for simple linear regression. For the modified Mann Kendall test, the magnitude of change in annual temperature is maximum in Uttarakhand (0.222 °C per decade) and minimum in Tripura (0.118 °C per decade).

India has highly diversified and spatially extensive states. Therefore, we also investigated seasonal temperature trends (*Rabi* season) at the district scale for 16 selected Indian districts from eight major wheat-producing Indian states: Uttar Pradesh, Punjab, Haryana, Madhya Pradesh, Bihar, Rajasthan, Gujarat, and Maharashtra. For this, we selected two representative districts (having minimum and maximum average seasonal temperature) in each of the major wheat-producing Indian states. Table 2 presents these 16 districts, their average seasonal temperature, and trends over 1966–2015 using simple linear regression (SLR) models and Mann Kendall (MK)/modified Mann Kendall (MMK) tests. It shows that Sitamarhi, Banas Kantha, Panchkula, Dindori, Nashik, Pathankot, Ganganagar, and Saharanpur have the minimum average seasonal temperature in Bihar, Gujarat, Haryana, Madhya Pradesh, Maharashtra, Punjab, Rajasthan, and Uttar Pradesh, respectively. On the other hand, Nalanda, Surat, Mewat, Burhanpur, Sindhudurg, Fazilka, Banswara, and Allahabad have the maximum average seasonal temperature in Bihar, Gujarat, Haryana, Madhya Pradesh, Maharashtra, Punjab, Rajasthan, and Uttar Pradesh, respectively. All 16 Indian districts show statistically significant rising temperature trends.

In our study, seasonal and annual temperatures demonstrate a significant increase across all Indian states. Rao *et al.* (2015) reported a rise in minimum temperature (at 0.32 °C per decade) and maximum temperature (at 0.28 °C per decade) in the wheat-growing areas of India (not a state-wise study). We estimated the temperature variation at the state level since the state is the most important administrative unit under the federal structure of India. Any adaptation strategy has to be implemented at the state level. Additionally, we also detected the temperature trends using non-parametric methods (i.e., Mann Kendall and modified Mann Kendall tests) that confirmed the rising temperature trends across Indian states.

Figure 2 shows the spatial distribution of seasonal temperatures (*Rabi* season) averaged over 50 years (1966–2015) across Indian states. It depicts that seasonal temperature declines as we move from the states in south India to north India. States located in south India (colored in red) have higher seasonal temperatures making them less preferred for wheat production. States located in the northern plains (Punjab, Haryana, and Uttar Pradesh; colored in yellow) have more favorable *Rabi* temperatures, making them vital wheat-producing Indian states. This spatial variation in seasonal temperature has profound implications for wheat production (as discussed in section 3.3. Climate-wheat yield relationships).

Table 1 | Summary output of simple linear regression (SLR) models and Mann Kendall (MK)/modified Mann Kendall (MMK) tests for trends in seasonal temperature (*Rabi* season) and annual temperature over 1966–2015 across Indian states

	Seasonal Temperature		Annual Temperature	
State	**Regression Coefficient of SLR Model (°C per decade)**	**Sen's Slope of MK/MMK Test (°C per decade)**	**Regression Coefficient of SLR model (°C per decade)**	**Sen's Slope of MK/MMK Test (°C per decade)**
Andhra Pradesh	0.219***	**0.199*****	0.185***	**0.179*****
Arunachal Pradesh	0.212***	0.184***	0.175***	**0.157*****
Assam	0.179***	**0.171*****	0.159***	**0.151*****
Bihar	0.231***	**0.232*****	0.201***	**0.215*****
Chhattisgarh	0.177***	0.192***	0.148***	0.147***
Goa	0.168***	0.155***	0.142***	**0.140*****
Gujarat	0.224***	**0.241*****	0.184***	**0.192*****
Haryana	0.197***	**0.180*****	0.159***	**0.160*****
Himachal Pradesh	0.243***	**0.250*****	0.195***	**0.199*****
Jammu and Kashmir	0.277***	**0.280*****	0.213***	**0.219*****
Jharkhand	0.179***	**0.188*****	0.159***	**0.178*****
Karnataka	0.203***	**0.190*****	0.174***	**0.167*****
Kerala	0.233***	**0.210*****	0.216***	**0.198*****
Madhya Pradesh	0.185***	0.188***	0.158***	0.159***
Maharashtra	0.172***	0.170***	0.140***	0.136***
Manipur	0.166***	**0.165*****	0.151***	**0.147*****
Meghalaya	0.140***	**0.133*****	0.135***	**0.135*****
Mizoram	0.116**	**0.106****	0.118***	**0.125*****
Nagaland	0.194***	**0.186*****	0.168***	**0.162*****
Odisha	0.140***	0.157***	0.123***	**0.137*****
Punjab	0.192***	**0.194*****	0.140***	**0.136*****
Rajasthan	0.231***	**0.235*****	0.182***	**0.177*****
Sikkim	0.259***	**0.233*****	0.222***	**0.211*****
Tamil Nadu	0.225***	**0.209*****	0.206***	**0.195*****
Telangana	0.208***	0.186***	0.173***	**0.164*****
Tripura	0.109**	**0.100****	0.112***	**0.118*****
Uttar Pradesh	0.229***	**0.224*****	0.201***	**0.207*****
Uttarakhand	0.247***	**0.248*****	0.214***	**0.222*****
West Bengal	0.146***	**0.133*****	0.138***	**0.152*****

*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$. Bold values indicate MMK test values (i.e., time series with significant autocorrelation).

3.2. Precipitation trends

We estimated the temporal variations in precipitation trends from 1966 to 2015 for India and each Indian state. Figure 3(a) shows that India's total seasonal precipitation (*Rabi* season) does not exhibit a significant trend (p=0.78) for a simple linear regression model. Mann Kendall testing confirmed a not significant trend in seasonal precipitation (Sen's slope=2.9 mm per decade, p=0.32). The minimum and maximum seasonal precipitation were 24 and 253 mm in 2001 and 1978, respectively, with a mean of 189 mm and a standard deviation of 28 mm from 1966 to 2015. Figure 3(b) shows the total annual precipitation for India also depicts a non-significant trend (p=0.91), ranging between 852 mm (in 1973) and 1,238 mm (in 2013),

Table 2 | Summary output of simple linear regression (SLR) models and Mann Kendall (MK)/modified Mann Kendall (MMK) tests for trends in seasonal temperature (*Rabi* season) over 1966–2015 across 16 selected districts from eight major wheat-producing Indian states

S. No.	State	District	Average Seasonal Temperature (°C)	Trend in Seasonal Temperature: Regression Coefficient of SLR Model (°C per decade)	Trend in Seasonal Temperature: Sen's Slope of MK/MMK Test (°C per decade)
1	Bihar	Sitamarhi	17.3	0.231***	**0.229*****
2	Bihar	Nalanda	22.9	0.198***	**0.188*****
3	Gujarat	Banas Kantha	23.8	0.266***	**0.272*****
4	Gujarat	Surat	26.5	0.197***	0.199***
5	Haryana	Panchkula	17.4	0.238***	**0.234*****
6	Haryana	Mewat	21.1	0.215***	**0.199*****
7	Madhya Pradesh	Dindori	21.6	0.184***	0.189***
8	Madhya Pradesh	Burhanpur	25.4	0.167***	0.160***
9	Maharashtra	Nashik	24.0	0.177***	0.182***
10	Maharashtra	Sindhudurg	27.0	0.201***	0.194***
11	Punjab	Pathankot	14.2	0.216***	**0.215*****
12	Punjab	Fazilka	20.6	0.212***	**0.226*****
13	Rajasthan	Ganganagar	20.6	0.207***	**0.203*****
14	Rajasthan	Banswara	24.4	0.218***	**0.231*****
15	Uttar Pradesh	Saharanpur	19.3	0.244***	**0.238*****
16	Uttar Pradesh	Allahabad	22.8	0.229***	**0.241*****

*p <0.1, **p <0.05, ***p <0.01. Bold values indicate MMK test values (i.e., time series with significant autocorrelation).

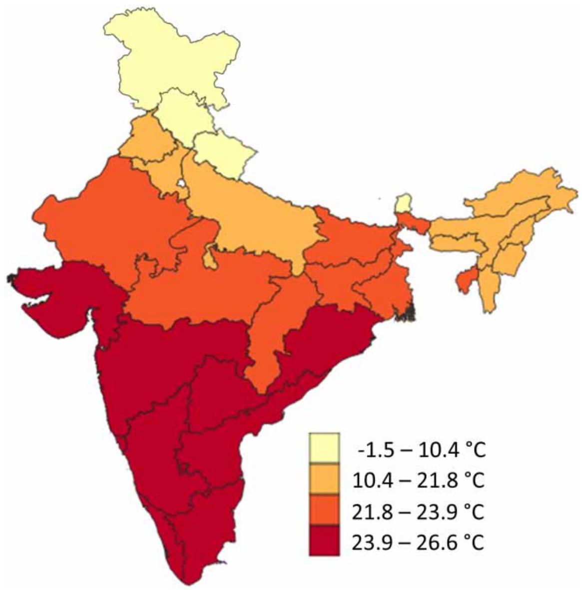

Figure 2 | Spatial distribution of seasonal temperature (*Rabi* season) averaged over 50 years (1966–2015) across Indian states.

with a mean of 1,072 mm and a standard deviation of 89 mm during 1966–2015. Mann Kendall testing again confirmed a not significant trend in annual precipitation (Sen's slope=-0.50 mm per decade, p=0.92).

To understand seasonal precipitation trends (over 1966–2015) for different Indian states, we fitted seasonal precipitations (*Rabi* season) in the linear regression models across Indian states (Supplementary Figure S3). We also applied Mann Kendall/

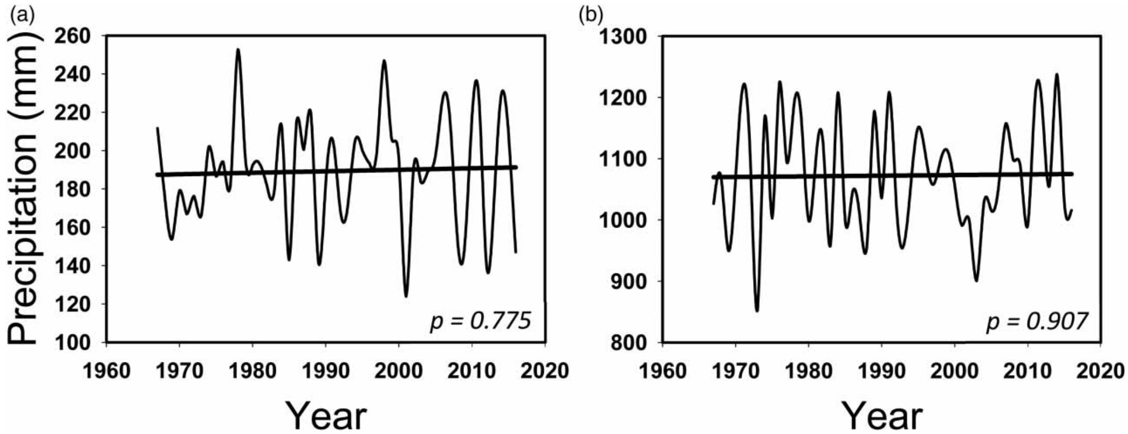

Figure 3 | Temporal variations in (a) seasonal precipitation (*Rabi* season) and (b) annual precipitation (May to April) for India from 1966 to 2015 using simple linear regression models.

modified Mann Kendall tests to detect trends in seasonal precipitations. Table 3 summarizes the regression coefficients, Sen's slopes, and the significance levels for the respective Indian states. We found that all Indian states demonstrate non-significant trends in seasonal precipitations for simple linear regression models. For Mann Kendall/modified Mann Kendall tests, only Arunachal Pradesh demonstrates a significant trend (Sen's slope=11.6 mm per decade). The magnitude of change in seasonal precipitation varies from -8.2 mm per decade (in Bihar) to 27.2 mm per decade (in Meghalaya) for simple linear regression. For the modified Mann Kendall test, the magnitude of change in seasonal precipitation varies from −7.7 mm per decade (in Bihar) to 17.6 mm per decade (in Meghalaya).

Similarly, we investigated the annual precipitation (May-April) trends over 1966–2015 across Indian states by fitting linear regression models (Supplementary Figure S4) and applying Mann Kendall/modified Mann Kendall tests. Table 3 shows that two Indian states – Uttar Pradesh and Uttarakhand – show statistically significant decreasing trends in annual precipitation. The remaining Indian states demonstrate non-significant trends in annual precipitation. For simple linear regression models, the magnitude of change in total annual precipitation varies between −47.5 mm per decade (in Uttarakhand) and 28.4 mm per decade (in Gujarat). For modified Mann Kendall tests, the magnitude of change in total annual precipitation varies from −67.3 mm per decade (in Mizoram) to 22.8 mm per decade (in Gujarat).

To investigate seasonal precipitation trends during *Rabi* season at district scale for major wheat-producing Indian states, we selected two representative districts, having minimum and maximum precipitation, from each of the eight major wheat-producing Indian states. Table 4 presents these 16 districts, their average seasonal precipitation, and trends over 1966–2015 using simple linear regression (SLR) models and Mann Kendall (MK)/modified Mann Kendall (MMK) tests. It shows that Buxar, Kheda, Mahendragarh, Alirajpur, Nandurbar, Mansa, Jaisalmer, and Agra have minimum average seasonal precipitation in Bihar, Gujarat, Haryana, Madhya Pradesh, Maharashtra, Punjab, Rajasthan, and Uttar Pradesh, respectively. On the other hand, Kishanganj, The Dangs, Panchkula, Seoni, Kolhapur, Pathankot, Dhaulpur, and Bahraich have maximum average seasonal precipitation in Bihar, Gujarat, Haryana, Madhya Pradesh, Maharashtra, Punjab, Rajasthan, and Uttar Pradesh, respectively. For simple linear regression, all the districts except Buxar (regression coefficient=−6.6 mm per decade) and Jaisalmer (regression coefficient=1.9 mm per decade) have non-significant trends. For Mann Kendall/modified Mann Kendall tests, all the districts demonstrate non-significant trends.

Recently, Ray & Goel (2021) analyzed long-term (1901–2013) spatio-temporal trends in precipitation over five different climatic regions of Northern India. The authors reported that more than 70% of rainfall datasets show non-significant trends. Tirkey *et al.* (2021) analyzed precipitation trends (1901–2013) in Himachal Pradesh. Kashyap & Agarwal (2021) reported that rainfall had a high uncertainty and variability over 1986–2017 in Ludhiana (Punjab, India), and consequently, irrigation water requirement has been highly fluctuating. However, no prior study investigated precipitation trends during the *Rabi* cropping season across all Indian states.

Figure 4 shows the spatial distribution of seasonal precipitation (*Rabi* season) averaged over 50 years (1966–2015) across Indian states. Indian states located in the far south and northeast receive higher seasonal precipitation during the *Rabi*

Table 3 | Summary output of simple linear regression (SLR) models and Mann Kendall (MK)/modified Mann Kendall (MMK) tests for trends in seasonal precipitation (*Rabi* season) and annual precipitation (May to April) over 1966–2015 across Indian states

	Seasonal Precipitation		Annual Precipitation	
State	**Regression Coefficient of SLR Model (mm per decade)**	**Sen's Slope of MK/MMK Test (mm per decade)**	**Regression Coefficient of SLR Model (mm per decade)**	**Sen's Slope of MK/MMK Test (mm per decade)**
Andhra Pradesh	2.8	−0.5	18.3	12.9
Arunachal Pradesh	8.2	11.6*	11.9	6.7
Assam	13.5	13.7	−1.2	−4.9
Bihar	−8.2	−7.7	−27.3	−19.4
Chhattisgarh	−3.0	−3.7	−6.9	−11.5
Goa	1.3	−4.7	11.6	−22.9
Gujarat	−0.6	0.1	28.4	22.8
Haryana	1.2	1.5	−6.0	−6.2
Himachal Pradesh	0.9	0.6	0.3	1.0
Jammu and Kashmir	0.5	0.2	7.3	8.1
Jharkhand	−7.0	−7.0	−26.8	−23.0
Karnataka	5.0	4.5	17.1	20.3
Kerala	18.3	16.0	−3.4	3.8
Madhya Pradesh	−3.8	−6.2	−6.6	−16.1
Maharashtra	1.1	−0.7	21.3	16.3
Manipur	4.1	3.5	−8.2	−17.4
Meghalaya	27.2	17.6	−20.5	−29.1
Mizoram	5.1	7.0	−31.6	−67.3
Nagaland	3.5	4.9	0.2	3.8
Odisha	−3.2	−6.2	12.8	17.4
Punjab	1.1	0.8	7.8	8.8
Rajasthan	1.1	−0.1	−1.4	0.6
Sikkim	−5.7	−2.2	0.8	−4.8
Tamil Nadu	9.8	9.3	12.9	12.9
Telangana	3.6	2.6	22.6	14.7
Tripura	14.6	12.9	−22.1	**−27.2**
Uttar Pradesh	−3.9	−4.2	−38.0**	−50.5**
Uttarakhand	−0.4	0.9	−47.5***	−41.3**
West Bengal	−4.7	−5.7	0.2	−10.9

$^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$. Bold values indicate MMK test values (i.e., time series with significant autocorrelation).

season. Excess *Rabi* rainfall in these states is detrimental to wheat production. Indian states in north-western and central parts of India receive comparatively less seasonal precipitation (*Rabi* season), including vital wheat-producing Indian states – Punjab, Haryana, and Uttar Pradesh. However, these vital wheat-producing Indian states also experience optimum (comparatively cooler) seasonal temperatures. These temporal trends and spatial variations in precipitation have crucial implications for wheat and agricultural production (as discussed in section 3.3. Climate-wheat yield relationships).

The climate trend analysis revealed that Indian states are witnessing a significant rise in seasonal and annual temperatures; and non-significant variations (except a few states) in seasonal and annual precipitations. Both parametric (i.e., linear regression analysis) and non-parametric methods (i.e., Mann Kendall, modified Mann Kendall, and Theil Sen's slope tests)

Table 4 | Summary output of simple linear regression (SLR) models and Mann Kendall (MK)/modified Mann Kendall (MMK) tests for trends in seasonal precipitation (*Rabi* season) over 1966–2015 across 16 selected districts from eight major wheat-producing Indian states

				Trend in Seasonal Precipitation	
S. No.	State	District	Average Seasonal Precipitation (mm)	Regression Coefficient of SLR Model (mm per decade)	Sen's Slope of MK/MMK Test (mm per decade)
1	Bihar	Buxar	94.2	−6.6*	−4.2
2	Bihar	Kishanganj	204.8	−8.2	−5.5
3	Gujarat	Kheda	22.4	−1.4	**−0.4**
4	Gujarat	The Dangs	80.8	1.1	1.7
5	Haryana	Mahendragarh	53.5	0.5	0.5
6	Haryana	Panchkula	160.3	1.7	2.1
7	Madhya Pradesh	Alirajpur	42.1	−1.4	−1.3
8	Madhya Pradesh	Seoni	144.9	−6.9	−6.6
9	Maharashtra	Nandurbar	56.1	−0.2	0.1
10	Maharashtra	Kolhapur	185.5	1.4	−2.4
11	Punjab	Mansa	65.9	0.9	1.3
12	Punjab	Pathankot	216.8	2.5	3.0
13	Rajasthan	Jaisalmer	20.5	1.9*	1.4
14	Rajasthan	Dhaulpur	59.7	0.4	−0.8
15	Uttar Pradesh	Agra	61.6	0.4	−1.0
16	Uttar Pradesh	Bahraich	155.1	−1.6	−2.4

*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$. Bold values indicate MMK test values (i.e., time series with significant autocorrelation).

detected that seasonal temperature (*Rabi* season) has increased significantly in all 29 Indian states. This temperature warming might present a serious challenge to Indian crop production. The findings suggested an opportunity to investigate further the relationship between temperature/precipitation trends and crop yields. So, we undertook the subsequent study (i.e., section 3.3.) to investigate climate-wheat yield relationships in India.

3.3. Climate-wheat yield relationships

3.3.1. Seasonal temperature and wheat yield

Figure 5(a) shows the results of correlation analysis between seasonal temperatures (*Rabi* season) and wheat yields across Indian states. Twenty-one Indian states – Andhra Pradesh*, Arunachal Pradesh, Assam, Bihar, Chhattisgarh, Gujarat, Haryana, Himachal Pradesh, Jammu & Kashmir, Jharkhand, Karnataka, Madhya Pradesh, Maharashtra, Odisha, Punjab, Rajasthan, Sikkim, Tripura, Uttar Pradesh, Uttarakhand, and West Bengal – demonstrate negative correlations between seasonal temperature and wheat yield. Nine out of these 21 Indian states – Chhattisgarh, Gujarat, Himachal Pradesh, Jharkhand, Karnataka, Madhya Pradesh, Maharashtra, Sikkim, and Uttarakhand (bars in black) show statistically significant negative correlations at $p<0.1$. Twelve Indian states – Andhra Pradesh*, Arunachal Pradesh, Assam, Bihar, Haryana, Jammu & Kashmir, Odisha, Punjab, Rajasthan, Tripura, Uttar Pradesh, and West Bengal (bars in grey) show statistically non-significant negative correlations. Only two Indian states, Meghalaya and Nagaland, have positive but non-significant correlation coefficients between wheat yield and seasonal temperature. In summary, the seasonal temperature has a negative impact on wheat yield in most of the Indian states.

We also estimated correlation coefficients of wheat yield with maximum and minimum seasonal temperatures (Figure 6). It shows that both maximum and minimum seasonal temperatures have statistically significant negative correlations with wheat yields in Chattisgarh, Gujarat, Himachal Pradesh, Jharkhand, Karnataka, Madhya Pradesh, and Maharashtra. Earlier, it was found that all these Indian states also showed significant negative correlations between mean seasonal temperatures and wheat yields (Figure 5). Figure 6 also indicates that Sikkim and Uttarakhand demonstrate a statistically significant negative correlation between wheat yield and maximum temperature only, leading to a significant negative correlation between wheat

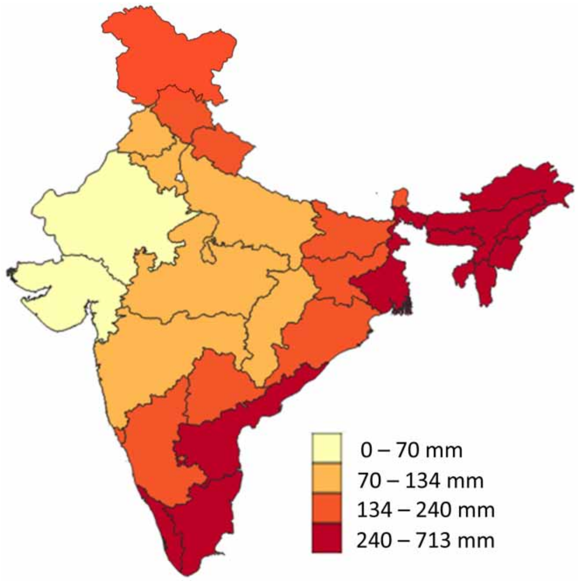

Figure 4 | Spatial distribution of seasonal precipitation (*Rabi* season) averaged over 50 years (1966–2015) across Indian states.

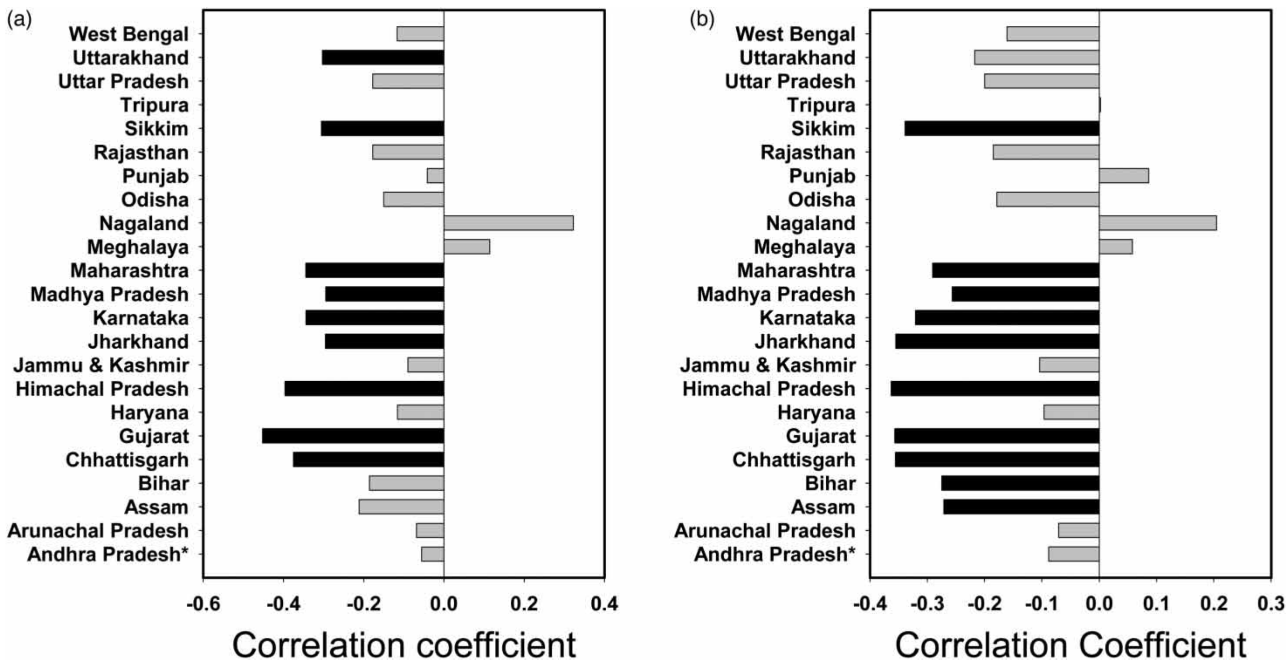

Figure 5 | Correlation coefficients between wheat yield and climate variables (a) seasonal temperature, (b) annual temperature. Bars in black color show significant correlations at $p<0.1$.

yield and mean temperature (Figure 5). Moreover, Assam, Bihar, and West Bengal only have a significant negative correlation between wheat yield and minimum seasonal temperature. No Indian state shows a statistically significant positive correlation of wheat yield with neither maximum nor minimum seasonal temperature. To further specifically understand the impact of maximum and minimum temperature on wheat yield, it would require undertaking separate extensive studies (state-wise), which are to be planned in the near future.

Table 5 shows correlation coefficients between seasonal temperature and wheat yield across 16 selected representative Indian districts in eight major wheat-producing Indian states. It shows that Banas Kantha (Gujarat), Nashik (Maharashtra),

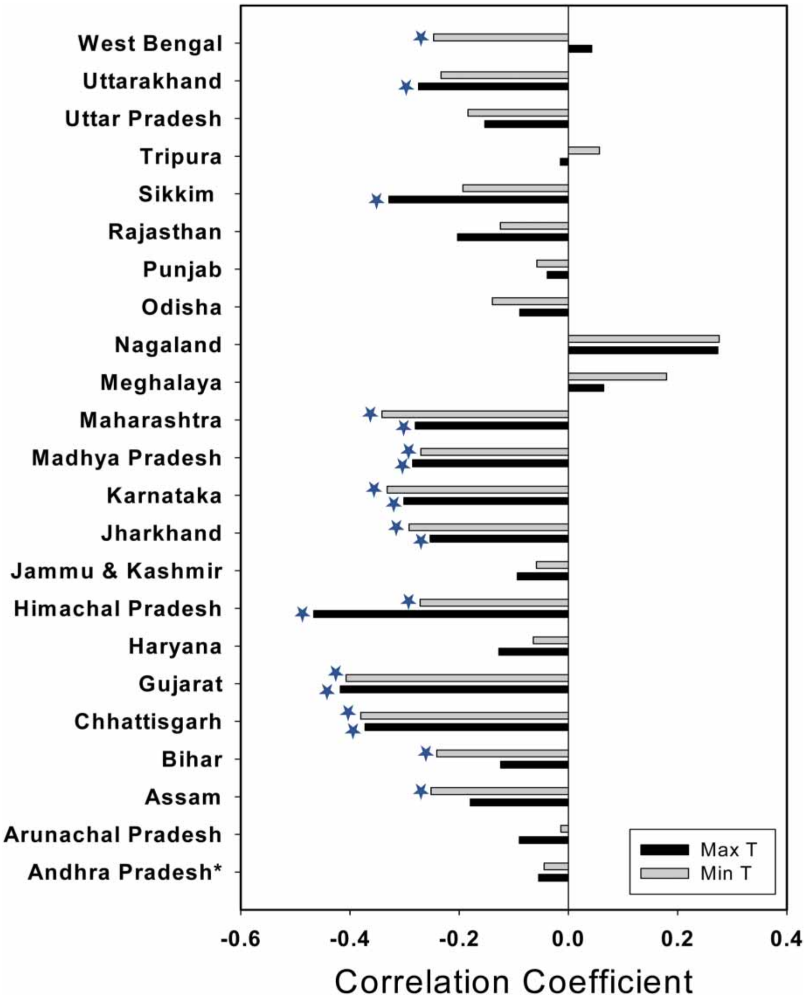

Figure 6 | Correlation coefficients of wheat yield with maximum temperature (Max T) and minimum temperature (Min T) during *Rabi* season. Stars in blue color show significant correlations at $p<0.1$.

and Banswara (Rajasthan) have statistically significant negative correlations between seasonal temperature and wheat yield. This is in harmony with the results of state-level correlation analysis between seasonal temperature and wheat yield that demonstrated statistically significant negative correlations for Gujarat and Maharashtra, and negative correlation for Rajasthan (Figure 5).

3.3.2. Annual temperature and wheat yield

Figure 5(b) shows the results of the correlation analysis between annual temperatures and wheat yields across Indian states. Nineteen Indian states – Andhra Pradesh*, Arunachal Pradesh, Assam, Bihar, Chhattisgarh, Gujarat, Haryana, Himachal Pradesh, Jammu & Kashmir, Jharkhand, Karnataka, Madhya Pradesh, Maharashtra, Odisha, Rajasthan, Sikkim, Uttar Pradesh, Uttarakhand, and West Bengal – have negative correlations between annual temperature and wheat yield. Ten out of these nineteen Indian states – Assam, Bihar, Chhattisgarh, Gujarat, Himachal Pradesh, Jharkhand, Karnataka, Madhya Pradesh, Maharashtra, and Sikkim (bars in black) show statistically significant negative correlations at $p<0.1$. The remaining nine Indian states – Andhra Pradesh*, Arunachal Pradesh, Haryana, Jammu & Kashmir, Odisha, Rajasthan, Uttar Pradesh, Uttarakhand, and West Bengal (bars in grey) – show statistically non-significant negative correlations. Four Indian states, Meghalaya, Nagaland, Punjab, and Tripura, show positive but statistically non-significant correlations between wheat yield and annual temperature.

Figure 7 depicts the spatial distribution of correlations between seasonal temperatures and wheat yields. Twenty-one Indian states, demonstrating a negative impact of seasonal temperature on wheat yield, account for ~99.85% of the wheat harvested

Table 5 | Correlation coefficients between seasonal temperature and wheat yield across 16 selected districts from eight major wheat-producing Indian states

S. No.	State	District	Correlation Coefficient
1	Bihar	Sitamarhi	−0.131
2	Bihar	Nalanda	−0.064
3	Gujarat	Banas Kantha	−0.488**
4	Gujarat	Surat	−0.089
5	Haryana	Panchkula	−0.041
6	Haryana	Mewat	0.190
7	Madhya Pradesh	Dindori	−0.362
8	Madhya Pradesh	Burhanpur	0.200
9	Maharashtra	Nashik	−0.503**
10	Maharashtra	Sindhudurg	Crop data not available
11	Punjab	Pathankot	0.234
12	Punjab	Fazilka	−0.358
13	Rajasthan	Ganganagar	−0.370
14	Rajasthan	Banswara	−0.533**
15	Uttar Pradesh	Saharanpur	0.118
16	Uttar Pradesh	Allahabad	0.149

**p* <0.1, ***p* <0.05, ****p* <0.01.

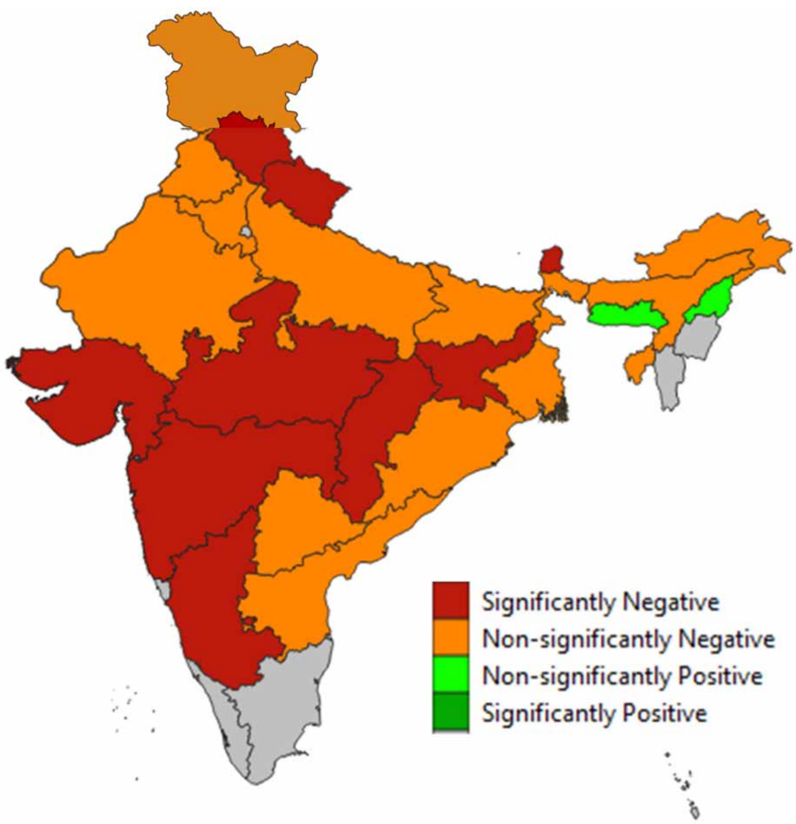

Figure 7 | Spatial distribution of correlations between seasonal temperatures and wheat yields over 1966–2015.

area (equivalent to ~24.1 million ha) in India over 1966–2015. Nine out of these 21 Indian states, showing statistically significant negative impact at $p<0.1$, account for ~27.30% of the wheat harvested area (equivalent to ~6.6 million ha) in India during 1966–2015. Seasonal temperature positively (non-significantly) impacts wheat yield in two northeast Indian states, Meghalaya and Nagaland. It was earlier reported that some parts of the world might witness beneficial effects of temperature rise on the wheat crop; however, the regions such as the Indo-Gangetic Plains, where optimum temperatures already exist, could see a reduction in wheat yields (Ortiz *et al.* 2008).

Our results, highlighting negative correlations between temperatures and wheat yields, are comparable with the earlier studies. Rising temperatures reduce the wheat development span, resulting in shorter spike differentiation and grain filling stages (Ahmad *et al.* 2021). Butterfield & Morison (1992) reported that a rise in surface air temperature leads to early flowering and shortening of the wheat's grain fill period, reducing total crop duration and yields. A shorter wheat development span also causes lower interception of solar radiation and reduced photosynthetic products, adversely affecting grains per ear and weight per grain of wheat (Shah & Paulsen 2003). Asseng *et al.* (2011) mentioned that thermal stress during grain filling speeds up wheat senescence and reduces grain yield. Lobell *et al.* (2012) reported a statistically significant hastening of wheat senescence from exposure to increased average temperatures in northern India. High temperature accelerates the metabolic rate and decelerates photosynthesis (Shah & Paulsen 2003). Temperature rise leads to an increase in evapotranspiration (i.e., evaporation losses), leading to soil moisture loss, causing yield loss due to water shortage and increased crop water demand (Kirkegaard *et al.* 2007). Indian wheat yields reduced by 7% (204 kg/ha) for a 1 °C increase in minimum temperature during 1980–2011 (Rao *et al.* 2015).

3.3.3. Monthly temperatures and wheat yield

Correlation analyses were also performed between monthly temperatures (during *Rabi* season) and wheat yield. The results enable us to identify critical months (during *Rabi* season) when monthly temperature significantly impacts wheat yield. The correlation coefficients vary from −0.531 to 0.402, and the following are crucial observations (Table 6):

- February temperature has a statistically significant negative impact on wheat yield across ten Indian states – Bihar, Chhattisgarh, Gujarat, Haryana, Jharkhand, Odisha, Punjab, Uttar Pradesh, Uttarakhand, and West Bengal.

Table 6 | Statistically significant correlation coefficients between monthly temperatures and wheat yield

State	Oct	Nov	Dec	Jan	Feb	Mar	Apr
Arunachal Pradesh	−0.353**	–	–	–	–	–	–
Assam	–	–	–	−0.257*	–	–	–
Bihar	–	−0.242*	–	–	−0.359**	–	–
Chhattisgarh	–	−0.238*	−0.274*	−0.357**	−0.375***	–	−0.268*
Gujarat	−0.252*	−0.270*	−0.410***	−0.531***	−0.349**		
Haryana	–	–	0.402***	–	−0.298**	–	−0.263*
Himachal Pradesh	–	–	–	–	–	−0.504***	−0.323**
Jharkhand	−0.260*	−0.352**	–	−0.275*	−0.358**	–	–
Karnataka	−0.240*	–	−0.335**	−0.287**	–	–	−0.422***
Madhya Pradesh	–	–	−0.265*	–	–	–	–
Maharashtra	–	−0.242*	−0.272*	−0.321**	–	–	−0.349**
Odisha	–	–	–	–	−0.305**	–	–
Punjab	–	–	0.381***	–	−0.323**	–	–
Sikkim	−0.433***	–	–	–	–	–	−0.390**
Uttar Pradesh	–	–	–	–	−0.342**	–	–
Uttarakhand	–	–	–	−0.358**	−0.449***	–	−0.282**
West Bengal	–	–	–	–	−0.315**	0.259*	–

*p <0.1, **p <0.05, ***p <0.01.

- January temperature has a statistically significant negative impact on wheat yield across seven Indian states – Assam, Chhattisgarh, Gujarat, Jharkhand, Karnataka, Maharashtra, and Uttarakhand.
- April temperature has a statistically significant negative impact on wheat yield across seven Indian states – Chhattisgarh, Haryana, Himachal Pradesh, Karnataka, Maharashtra, Sikkim, and Uttarakhand.
- October temperature has a statistically significant negative impact on wheat yield across five Indian states – Arunachal Pradesh, Gujarat, Jharkhand, Karnataka, and Sikkim.
- November temperature has a statistically significant negative impact on wheat yield across five Indian states – Bihar, Chhattisgarh, Gujarat, Jharkhand, and Maharashtra.
- December temperature has a statistically significant negative impact on wheat yield across five Indian states – Chhattisgarh, Gujarat, Karnataka, Madhya Pradesh, and Maharashtra.
- March temperature has a statistically significant negative impact on wheat yield in one Indian state, i.e., Himachal Pradesh.

We observe that February temperature has the most detrimental effect on wheat yield in the maximum number of Indian states. It is because wheat enters the maturity stage during February and becomes more susceptible to temperature rise than the earlier growth stages during October-November. Earlier, Farooq *et al.* (2011) mentioned that wheat is more sensitive to high temperature during the maturity stage than the earlier stages. Temperature rise reduces photosynthesis and increases wheat senescence during the maturity stage (Lobell *et al.* 2012). It causes early wheat ripening, shortens the grain filling and maturity periods, and thus reduces the total wheat growth duration (Akter & Islam 2017). Therefore, temperature stress reduces grain size, the number of grains per spike, and grain quality during the maturity stage (Riaz *et al.* 2021).

To summarize, warming presents a serious challenge to Indian wheat production. Wheat yield reductions due to warming could substantially undermine future Indian food security. So, the Indian government and farmers need to adopt appropriate crop management practices and heat-tolerant wheat cultivars to address the negative impact of heat stress on wheat yields.

3.3.4. Seasonal precipitation and wheat yield

After temperature, we performed correlation analyses between precipitations and wheat yields. Figure 8(a) presents the correlation coefficients between seasonal precipitation and wheat yield across Indian states. Fifteen Indian states – Arunachal Pradesh, Bihar, Chhattisgarh, Gujarat, Haryana, Himachal Pradesh, Jammu & Kashmir, Jharkhand, Karnataka, Madhya

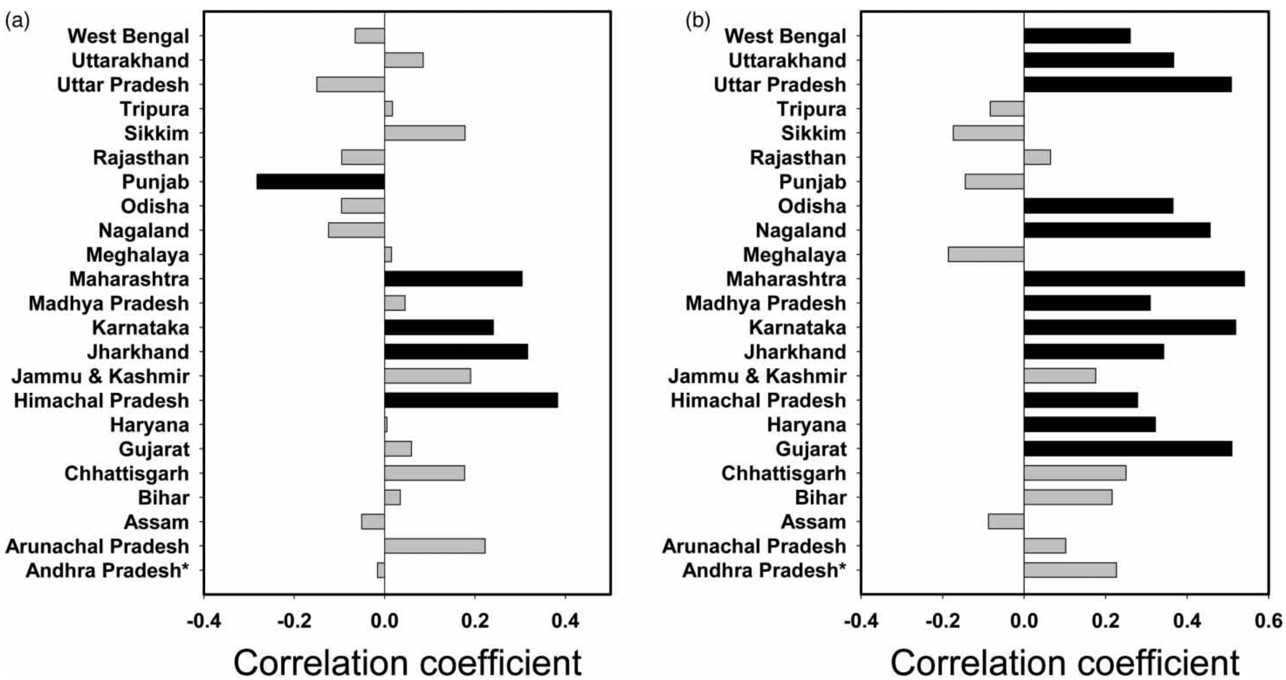

Figure 8 | Correlation coefficients between wheat yield and climate variables (a) seasonal precipitation, (b) annual precipitation. Bars in black color show a significant correlation at $p<0.1$.

Pradesh, Maharashtra, Meghalaya, Sikkim, Tripura, and Uttarakhand – show positive correlations between seasonal precipitation and wheat yield. Four of these 15 Indian states – Himachal Pradesh, Jharkhand, Karnataka, and Maharashtra (bars in black) – show statistically significant positive correlations at $p<0.1$. Eleven Indian states – Arunachal Pradesh, Bihar, Chhattisgarh, Gujarat, Haryana, Jammu & Kashmir, Madhya Pradesh, Meghalaya, Sikkim, Tripura, and Uttarakhand (bars in grey) – show statistically non-significant positive correlations.

Eight Indian states – Andhra Pradesh*, Assam, Nagaland, Odisha, Punjab, Rajasthan, Uttar Pradesh, and West Bengal – show negative correlations between seasonal precipitation and wheat yield. Punjab (bar in black) shows a statistically significant negative correlation at $p<0.1$. Andhra Pradesh*, Assam, Nagaland, Odisha, Rajasthan, Uttar Pradesh, and West Bengal (bars in grey) show statistically non-significant negative correlations. In summary, 15 Indian states demonstrate a positive impact, and 8 Indian states demonstrate a negative impact of seasonal precipitation on wheat yield. Table 7 shows correlation coefficients between seasonal precipitation and wheat yield across 16 selected districts in eight major wheat-producing Indian states. It shows that 10 districts demonstrate negative correlations, whereas 6 districts have positive correlations between seasonal precipitation and wheat yield. Only Bahraich (Uttar Pradesh) has a statistically significant negative correlation between seasonal precipitation and wheat yield.

3.3.5. Annual precipitation and wheat yield

Figure 8(b) presents the bivariate correlation coefficients between annual precipitation and wheat yield across Indian states. It shows that 18 Indian states – Andhra Pradesh*, Arunachal Pradesh, Bihar, Chhattisgarh, Gujarat, Haryana, Himachal Pradesh, Jammu & Kashmir, Jharkhand, Karnataka, Madhya Pradesh, Maharashtra, Nagaland, Odisha, Rajasthan, Uttar Pradesh, Uttarakhand, and West Bengal – demonstrate positive correlations between annual precipitation and wheat yield. Twelve out of these 18 Indian states – Gujarat, Haryana, Himachal Pradesh, Jharkhand, Karnataka, Madhya Pradesh, Maharashtra, Nagaland, Odisha, Uttar Pradesh, Uttarakhand, and West Bengal (bars in black) – show statistically significant positive correlations at $p<0.1$. The remaining six Indian states – Andhra Pradesh*, Arunachal Pradesh, Bihar, Chhattisgarh, Jammu & Kashmir, and Rajasthan (bars in grey) – show statistically non-significant positive correlations. Five Indian states – Assam, Meghalaya, Punjab, Sikkim, and Tripura – show negative and non-significant correlations between wheat yield and total annual precipitation.

Table 7 | Correlation coefficients between seasonal precipitation and wheat yield across 16 selected districts from eight major wheat-producing Indian states

S. No.	State	District	Correlation Coefficient
1	Bihar	Buxar	−0.198
2	Bihar	Kishanganj	0.150
3	Gujarat	Kheda	−0.047
4	Gujarat	The Dangs	0.080
5	Haryana	Mahendragarh	0.338
6	Haryana	Panchkula	−0.191
7	Madhya Pradesh	Alirajpur	−0.408
8	Madhya Pradesh	Seoni	−0.113
9	Maharashtra	Nandurbar	−0.026
10	Maharashtra	Kolhapur	0.227
11	Punjab	Mansa	−0.106
12	Punjab	Pathankot	−0.811
13	Rajasthan	Jaisalmer	−0.186
14	Rajasthan	Dhaulpur	0.086
15	Uttar Pradesh	Agra	0.144
16	Uttar Pradesh	Bahraich	−0.423*

*$p<0.1$, **$p<0.05$, ***$p<0.01$.

Comparing Figures 8(a) and 8(b), we observe that the annual precipitation has a more positive impact on wheat yield across Indian states than seasonal precipitation. Precipitation before wheat's sowing (i.e., during Monsoon months, June-September) increases the soil moisture, helping overall wheat production. Mukherjee *et al.* (2019) reported that a decrease in monsoon rainfall during July–August causes a depletion in groundwater levels in Northwest India and leads to wheat yield reduction.

Figure 9 depicts the spatial distribution of correlations between seasonal precipitation and wheat yield across Indian states. Fifteen Indian states, demonstrating a positive impact of seasonal precipitation on wheat yield, account for ∼43.62% of the wheat harvested area (equivalent to ∼10.5 million ha) in India over 1966–2015. *Rabi* season in most Indian states is the dry season, and the precipitation meets the water demand of wheat; that is why there are positive effects in many Indian states. A moderate positive relationship between wheat yield and seasonal rainfall during the wheat growing season in Ethiopia was reported by Bekele *et al.* (2017). The study in southern Australia showed that wheat yield potential had decreased by 27% over 1990–2015, and about 75% of this decline was attributed to a decrease in rainfall (Hochman *et al.* 2017).

We observe that eight Indian states, demonstrating a negative impact of seasonal precipitation on wheat yield, account for ∼56.26% of the wheat harvested area (equivalent to ∼13.6 million ha) in India over 1966–2015. Seasonal precipitation has a negative impact on a relatively larger wheat-producing area (∼56.26% *vs.* ∼43.62%). Among the Indian states having adverse effects, some are in the northwest (e.g., Punjab), some are in the northeast and east parts of India, where seasonal precipitation is higher than the water requirement of wheat.

Comparing the impacts of seasonal precipitation (Figure 9) and seasonal temperature (Figure 7), we find that seasonal precipitation has an adverse impact on wheat yield in a lesser number of states than seasonal temperature. As per Naresh Kumar *et al.* (2014), >85% of the wheat harvested area is irrigated in India; therefore, the impact of precipitation is not so significant. The adverse effects of low precipitation can be partly mitigated by artificial irrigation facilities (Vogel *et al.* 2019), but it is relatively challenging to address the impact of rising temperatures. Additionally, temperature trends in India are more pronounced and significant than the precipitation trends, as discussed in sections 3.1. and 3.2.

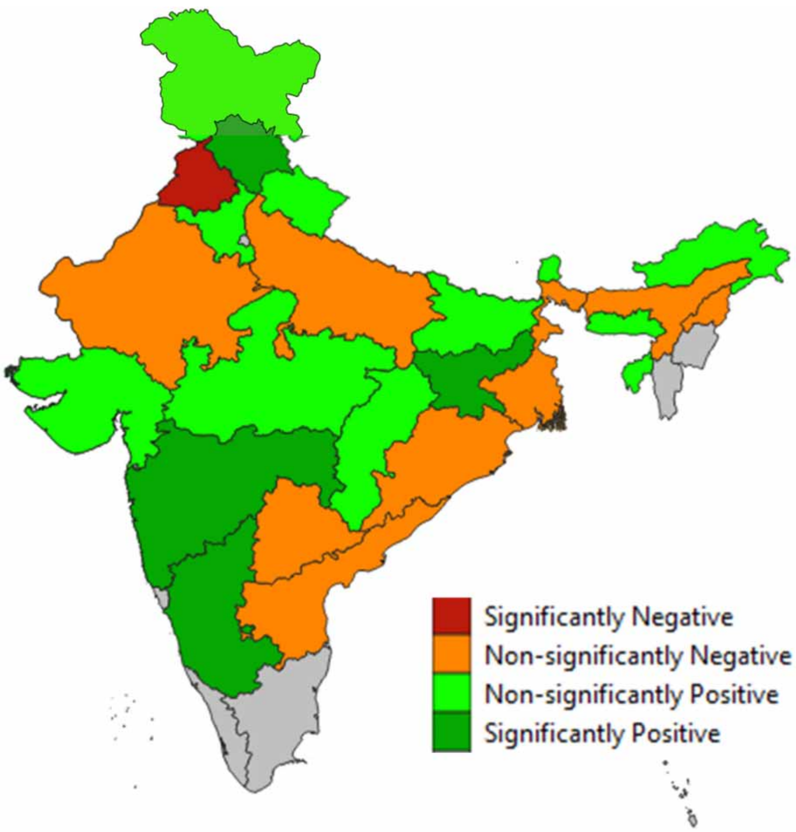

Figure 9 | Spatial distribution of correlation between seasonal precipitation and wheat yield over 1966–2015.

3.3.6. Monthly precipitations and wheat yield

Correlation tests were also conducted between monthly precipitations (during *Rabi* season) and wheat yields. The results enable us to identify critical months (during *Rabi* season) when monthly precipitation significantly impacts wheat yield. The correlation coefficients vary from -0.489 to 0.382, and the following are some crucial observations (Table 8):

- March precipitation has a statistically significant negative impact on wheat yield across seven Indian states – Bihar, Haryana, Odisha, Punjab, Uttar Pradesh, Uttarakhand, and West Bengal. November precipitation displays a statistically significant negative impact in two Indian states, Madhya Pradesh and Punjab. February precipitation demonstrates a statistically significant negative impact in Nagaland. December precipitation displays a statistically significant negative impact in Maharashtra. April precipitation shows a statistically significant negative impact on wheat yield in Bihar.
- January precipitation has a statistically significant positive impact on wheat yield across four Indian states – Assam, Jammu & Kashmir, Jharkhand, and Madhya Pradesh. Also, January precipitation does not significantly negatively correlate with wheat yield in any Indian state. October precipitation displays a statistically significant positive impact on wheat yield in three Indian states, Arunachal Pradesh, Jharkhand, and Maharashtra. March and April precipitation show statistically significant positive effects in two Indian states (Himachal Pradesh and Karnataka) and one Indian state (Karnataka).
- To summarize, March precipitation has an adverse impact on the wheat yield in the highest number of states, whereas January precipitation has a positive effect on the wheat yield in the highest number of Indian states.

The key wheat-producing states, Uttar Pradesh, Haryana, and Punjab, have statistically significant negative correlations between wheat yield and March precipitation, i.e., −0.485, −0.274, and −0.320, respectively. March precipitation also negatively impacts (statistically significantly) wheat yield in West Bengal, Bihar, and Odisha, having correlation coefficients of −0.429, −0.386, and −0.250, respectively. To further understand the impact of precipitation on wheat yield, it is noteworthy to mention that a wheat plant undergoes four growth stages: (1) pre-establishment stage, (2) vegetative stage, (3) reproductive stage, and (4) post-anthesis stage. The effect of precipitation is not the same in all these growth stages. March precipitation hampers the wheat plant's earing, flowering, and grain filling stages, causing wheat yield loss. During the post-anthesis (grain filling and maturity) stage, waterlogging causes high disease probability and reduces wheat yield (Tafoughalti *et al.* 2018). In contrast, January precipitation positively impacts wheat yield in most Indian states when the wheat plant is in the stage of

Table 8 | Statistically significant correlation coefficients between monthly precipitations and wheat yield

State	Oct	Nov	Dec	Jan	Feb	Mar	Apr
Arunachal Pradesh	0.287*	–	–	–	–	–	–
Assam	–	–	–	0.286*	–	–	–
Bihar	–	–	–	–	–	−0.386***	−0.253*
Haryana	–	–	–	–	–	−0.274*	–
Himachal Pradesh	–	–	–	–	–	0.349**	–
Jammu & Kashmir	–	–	–	0.255*	–	–	–
Jharkhand	0.361**	–	–	0.286**	–	–	–
Karnataka	–	–	–	–	–	0.272*	0.280**
Madhya Pradesh	–	−0.289**	–	0.251*	–	–	–
Maharashtra	0.382***	–	−0.239*	–	–	–	–
Nagaland	–	–	–	–	−0.489**	–	–
Odisha	–	–	–	–	–	−0.250*	–
Punjab	–	−0.273*	–	–	–	−0.320**	–
Uttar Pradesh	–	–	–	–	–	−0.485***	–
Uttarakhand	–	–	–	–	–	−0.276*	–
West Bengal	–	–	–	–	–	−0.429***	–

*p <0.1, **p <0.05, ***p<0.01.

elongation and booting. During the vegetative and reproductive stages, rainfall helps the root yield, fertilization, and grain survival (Tafoughalti *et al.* 2018).

3.4. Wheat yield variability explained by climate variability

The coefficient of determination (R^2) in a regression model signifies how much variation in the response variable (i.e., wheat yield) is explained by the explanatory variables (i.e., climate variables). We employed four climate variables–seasonal temperature (*ST*), annual temperature (*AT*), seasonal precipitation (*SP*), and annual precipitation (*AP*)–in various regression models, as discussed in section 2.7: Regression models. The state-wise best-fit models were selected using the Akaike Information Criterion (AIC), and their coefficient of determination (R^2) was estimated as presented in Table 9. It shows that the regression models for 22 Indian states are significant. Fifteen out of these 22 Indian states have statistically significant regression models at $p<0.01$. Four out of the 22 Indian states have statistically significant regression models at $p<0.05$. Three out of 22 Indian states have statistically significant regression models at $p<0.1$. Tripura has a non-significant regression model. Climate variability explains:

- >40% of the wheat yield variability in six Indian states – Assam, Gujarat, Nagaland, Punjab, Sikkim, and Uttarakhand.
- 20–40% of the wheat yield variability in five Indian states – Bihar, Himachal Pradesh, Karnataka, Maharashtra, and Uttar Pradesh.
- 10–20% of the wheat yield variability in nine Indian states – Andhra Pradesh*, Arunachal Pradesh, Chhattisgarh, Haryana, Jammu & Kashmir, Jharkhand, Madhya Pradesh, Odisha, and Rajasthan.
- <10% of the wheat yield variability in Meghalaya and West Bengal.
- Overall, seasonal and annual climate variables account for 7 to 78% of the wheat yield variability across Indian states.

Table 9 | State-wise best-fit regression models with coefficients of determination (R^2), *p* value, and significance level

State	Best-fit model	R^2	*p* value
Andhra Pradesh*	Precipitation only	0.15	0.0047***
Arunachal Pradesh	Temperature only	0.12	0.0248**
Assam	Complex	0.44	0.0076***
Bihar	Complex	0.32	0.0088***
Chhattisgarh	Temperature only	0.18	0.0023***
Gujarat	Temperature and Precipitation model	0.55	<0.0001***
Haryana	Precipitation only	0.10	0.0229**
Himachal Pradesh	Temperature only	0.20	0.0012***
Jammu & Kashmir	Precipitation only	0.19	0.0079***
Jharkhand	Temperature only	0.17	0.0030***
Karnataka	Temperature and Precipitation model	0.38	0.0002***
Madhya Pradesh	Precipitation only	0.14	0.0253**
Maharashtra	Precipitation only	0.30	<0.0001***
Meghalaya	Precipitation only	0.08	0.0521*
Nagaland	Complex	0.78	0.0109**
Odisha	Precipitation only	0.18	0.0092***
Punjab	Complex	0.43	0.0034***
Rajasthan	Temperature and Precipitation model	0.18	0.0580*
Sikkim	Temperature and Precipitation model	0.49	0.0026***
Tripura	Precipitation only	0.03	0.2445
Uttar Pradesh	Precipitation only	0.36	<0.0001***
Uttarakhand	Temperature and Precipitation model	0.47	0.0001***
West Bengal	Precipitation only	0.07	0.0676*

*$p<0.1$, **$p<0.05$, ***$p<0.01$.

3.5. Implications for future studies

This study found that temperature and precipitation have negative impacts on wheat yield across many Indian states. Wheat is a primary food crop in India that provides food security and livelihood to millions of Indians. Therefore, the negative climatic impacts on wheat might lead to severe ramifications for socio-economic development. Moreover, climatic effects on wheat yield are heterogenous across Indian states, i.e., they vary from state to state. Therefore, state-level planning and decentralized/customized efforts are required to identify appropriate mitigation strategies to address climate impacts on wheat yield in India. Future studies might pursue such investigations on different adaptation strategies to address climate impacts on wheat yields.

For example, a change in sowing time has been an interesting adaptation measure. An early-sown region is expected to suffer less than a late-sown region. The sowing dates for wheat crops in northwest India are relatively early compared to the eastern part of India. Though early sowing may decrease or avoid heat damage in the grain filling stage, a relatively high temperature during sowing (in the case of early sowing) may adversely affect seedling vitality. Further, late sowing might improve the climate condition for seedling vitality but will increase heat damage in the grain filling stage. So, it seems there are pros and cons associated with both early and late sowing approaches, and there is no 'one size fits all' solution. Similarly, breeding varieties with heat/water resistance is another important adaptation measure. Water-saving irrigation and soil moisture conservation farming are also essential in arid areas lacking irrigation. The researchers can further investigate these adaptation measures as part of their future studies.

We have investigated temperatures and precipitation in this study but did not include an increased level of air pollution (i.e., increased level of CO_2, ozone, particulate matters) that might influence wheat yields. These two aspects, i.e., changing climate variables and rising air pollution levels, might offset or enhance each other's impact on crop yields. Therefore, an investigation of the effects of air pollution on crop yields is also suggested for future research work.

4. CONCLUSION

Seasonal temperature (*Rabi* season) has increased significantly in all the 29 Indian states, and demonstrated a negative impact across 21 Indian states, affecting ~99.85% of the wheat harvested area (equivalent to ~24.1 million hectares) in India. February temperature has the most detrimental impact (affecting the reproductive stage) on wheat yield in the maximum number of Indian states. Seasonal precipitation (*Rabi* season) has non-significantly decreased and increased in ten and 19 Indian states, respectively, and demonstrated a negative impact across eight Indian states, affecting ~56.26% of the wheat harvested area (equivalent to ~13.6 million hectares) in India. March precipitation has the most severe impact on wheat yield (interfering with the post-anthesis stage). The present study revealed that large wheat harvested area in India is facing adverse effects of temperature and precipitation. Climate variability accounted for up to ~78% of the wheat yield variability across Indian states. These findings present an opportunity for policy makers to develop customized adaptation strategies and measures to mitigate climate effects, ensuring sustained wheat yield growth and production.

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CONFLICTS OF INTEREST/COMPETING INTERESTS

On behalf of all authors, the corresponding author states that there is no conflict of interest. The authors are not affiliated with or involved with any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this paper.

DATA AVAILABILITY STATEMENT

All relevant data are available from http://www.cru.uea.ac.uk/ and https://eands.dacnet.nic.in/.

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