Theoretical and Applied Climatology (2022) 150:1531–1544
https://doi.org/10.1007/s00704-022-04246-7

ORIGINAL PAPER

# Rising winter temperatures might augment increasing wheat yield in Gangetic Plains

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Received: 4 March 2022 / Accepted: 11 October 2022 / Published online: 21 October 2022


**Abstract**

The changing climate poses significant stress on the yield of wheat, which is a major grain crop in Gangetic Plain and therefore on the food security of this densely populated region. Here, we aim to assess the effects of different climate parameters on wheat yield in the last four decades. The redundancy analysis (RDA) shows that the climatic factors could explain up to 35% of the variations in the wheat yield. The negative correlation with precipitation, Palmer Drought Severity Index (PDSI) and Standardized Precipitation Evapotranspiration Index (SPEI) in winter months might be associated with extreme wetting that delays the yield during the seeding and late growth stages. We recorded a positive and statistically significant correlation between wheat yield and previous year winter mean temperature. The analysis shows that the increase in temperature during the seedling and the late growth stage may result in maximum yield. The linear relationship with the yield in the study area is statistically significant with temperature rise during 1971–2011. The yield of wheat shows a significant positive relationship with both air temperature and sea surface temperature (SST) during winter months in and around India and over the seas regulating winter climate. This indicates that winter temperature may have a direct role in modulating the yield of wheat in the Gangetic Plain demanding further implications of temperature rise on wheat production in future.

## 1 Introduction

Globally, India ranks third in wheat production, after the European Union and China, making wheat a major staple food crop of the country (Clay 2002). Apart from the soil quality and spatial diversity, the yield of wheat is primarily controlled by the variation in climate parameters line temperature, sunshine hours, rainfall, and the regional availability of moisture (Aggarwal 2008a, b; IPCC 2014). The Gangetic Plains and Central India are the major wheat producing regions in Asia (Smale and McBride 1996). A major portion of the wheat production in India comes from northwest of the Gangetic Plain (Kumar et al. 2014; Singh and Mustard 2012). The annual wheat production in India is ~85.7 Mt (Megatonne) which is around 36% of annual food grain production (Kumar et al. 2014). The all-time highest output of 99.70 Mt of wheat (13.64% of world production) with a record average productivity of 3371 kg/ha was recorded during 2017–2018 C.E. The annual yield of wheat in India has shown an increasing trend, from 87.39 Mt (in 2012–2013) to 94.57 Mt (in 2017–2018) with a magnitude of 7.18 Mt (8.22%). Around 85 Mt (90%) of wheat has been produced from the main wheat-growing states such as Uttar Pradesh, Punjab, Haryana, Madhya Pradesh, Bihar, and Rajasthan (Ramdas et al. 2013). The contribution of this cereal crop mostly confines to the northern states of India, where Uttar Pradesh (UP) is the highest contributor, with a total wheat production of 25.22 Mt followed by Punjab (15.78 Mt) and Madhya Pradesh (14.18 Mt) (GoI 2021). UP is the largest producer of wheat in the country accounting for about 28 Mt per year which is roughly 30% of the total annual production. However, UP, despite having the largest land area used for wheat sowing (9.85 million ha), has the productivity (2561 kg/ha) that is less than the national average which is approximately 3.5 Mt/ha (DoES 2021).

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There have been several attempts to assess the yield of crops under different climate change scenarios (Kumar et al. 2012, 2014; Lal et al. 1998). Studies on agricultural production under different climate scenarios in India project a systematic decline in the annual yield. An increase in temperature by 1 °C was projected to reduce the annual wheat production in India by 4–5 Mt, even after contemplating the complimentary effect of $CO_2$ fertilization (Aggarwal, 2008a, b). However, the production of this crop has increased significantly in the last decade, defying all the projections, mainly due to the recent uncertainty in climate scenarios (IPCC, 2014). Uncertainty in climate scenarios here refers to the inability to predict the scale, intensity, and impact of climate change on human and natural environments (Mehta et al. 2019). This inconsistency may be attributed to a range of factors, e.g., technological development, raise of new varieties, and high use of manure and pesticides in addition to the projected increase in temperature. There are studies which suggest that the current warming climate may alter the amount, intensity, frequency, and form of precipitation in different parts of the globe (Goswami et al. 2006; IPCC, 2014; Rajeevan et al. 2008). It is believed that the association with recent climate change in terms of increasing temperature and uncertainty of precipitation is expected to adversely affect the agriculture production (Houghton et al. 2001). Thus, a major question of how the yield of wheat would respond to the ongoing warming scenario of the climate needs to be addressed.

The average wheat yield doubled between 1980 and 2010 C.E., although the rate of yield increase accelerated significantly after the end of 1990s (Clay, 2002). The reasons behind the recent increase in the annual yield of wheat are associated with crop management in addition to the climatic factors. This increase in wheat yield since 1980 is also attributed to the adoption of technological and management improvements, such as minimum tillage, soil amelioration, stubble retention, early sowing, and integrated weed control. During late 1960s, India adopted a new nationwide strategy, also known as the Green Revolution, which led to initiatives such as introduction of semi dwarf wheat variety like Sonara 64, Lema Roja, and Sonalika (Dalrymple, 1974). In addition, this also led to increased reliance on agricultural machinery (for example, use of tractor) particularly in the states of UP, Punjab and Haryana in the production of wheat and rice. Since then, coordinated research and several developmental and food security-based programmes in various phases have made the nation to progress closer towards food and nutrition for all by achieving record and surplus production of wheat. The wheat cultivation area at national level has significantly increased during 2008–2013, from 29.04 million to 30.54 million ha with 1.5 million ha (5%) net gain. The production of wheat has also showed an increasing trend, from 87.39 to 94.57 million tonnes from 2012–2013 to 2017–2018 with a magnitude of 7.18 million tonnes (8.22%) (Ramadas et al. 2019). UP has largest share in area with 9.75 million ha (32%), followed by Madhya Pradesh (18.75%), Punjab (11.48%), Rajasthan (9.74%), Haryana (8.36%) and Bihar (6.82%) (Ramadas et al. 2019). However, a major expansion in wheat sowing area was observed in the states such as Jharkhand (51%), Madhya Pradesh (27%) and Rajasthan (13%) (ICAR, 2021). Moreover, the increase in wheat yield were not uniform across the Indian states; the greatest increases were in UP, MP, Haryana and Punjab (Joshi et al. 2007).

The maximum yield of wheat can be achieved if the climate is moderate (20–25 °C) and humid (50–60%) during the germination period with a bit increase in temperature by the ripening period (GoI, 2022). Climate change and its impact on growth and yield are explored through various crop simulation models using different stress conditions (Tashiro and Wardlaw, 1990), but the long-term assessment of global teleconnection with regional wheat production are still missing for the Indian Subcontinent and its largest producer, the Gangetic Plain. Therefore, it is important to understand the response of wheat productivity to seasonal and monthly climate and moisture variables for the Gangetic Plain. The better understanding of impacts of climate change on crop yields will help in improving the productivity. In the present study, we selected five high wheat producing districts of UP, the most populous and the largest wheat producing state of India and constituting the largest part of the Gangetic Plain. This sampling was based on long-term and reliable data availability to study the temporal yield and climate relationship for wheat production. This study is based on the correlation and redundancy analysis (RDA) of wheat yield for the five districts of UP with different climatic parameters (e.g., mean, maximum, and minimum temperatures, and precipitation) as well as moisture indices such as, Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al. 2010) and Palmer Drought Severity Index (PDSI) (Palmer, 1965) to understand moisture variability. The present study is an attempt to understand the limiting factors in the climatic variables that control the yield of wheat, and its long-term relationship with atmospheric circulation. This study further tries to understand the long-term teleconnection of yield data with moisture index and Sea surface temperature (SST). These results could be used to better evaluate future wheat production under the present change in the global climate.

## 2 Materials and methods

### 2.1 Study area

The five districts of UP selected for the present study are Kanpur, Banda, Jhansi, Faizabad, and Lucknow (Fig. 1). The yearly wheat production data for these districts from 1971 to 2011 C.E. is acquired from the published record of the Directorate of Economics and Statistics, Ministry of Agriculture and Farmer Welfare (DoES, 2021). The five districts which we have selected for the present study sample are the largest contributors of wheat production in UP. The wheat production in UP is distributed across three agroclimatic zones which are Western UP (3.29 Mha), Eastern UP (5.24 Mha), and Central UP (0.68 Mha) (ICAR, 2021). Additionally, based on the precipitation pattern, the study sites have been divided into two regions, which are Region A which includes Kanpur, Lucknow, Faizabad, Banda, and Region B which includes Jhansi. The past climate data shows that the mean annual precipitation (MAP) and mean annual temperature (MAT) in Region A is ~1013 mm and 25.9 °C while for Region B it is 978 mm and 25.6 °C, respectively. The temperature in Region A varies between 7.9 and 42.1 °C while in Region B it varies between 8.5 and 42.3 °C (Fig. 2). The region B receives significantly less precipitation compared to the other four districts making the climate semi-arid and that is why it is important to understand the interrelationship between climate parameters and wheat yield separately for this region (Fig. 2). The primary source of rainfall in the region is the Indian summer monsoon, which is the South-West Monsoon while in the winters the rainfall is caused due to the Western Disturbances and North-East Monsoon (IDUP, 2021). The soils of both regions are characterized by their varying depth, topographic situation, and colour. The main soil groups are silty clay loam, silty loam, and loamy for Region A, and red and black soil for Region B (DoA, 2021).

## 2.2 Phenology of wheat

The phenology of wheat, from sowing of seeds to the harvesting of crop, is dependent on the seasonal change in temperature (DoA, 2021). In UP, wheat is usually sown during late October to November and is harvested from April to May depending on the seasonal weather condition (DoA, 2021). Past studies suggest that the physiological and morphological development of the crop from sowing to maturity is mainly affected by the temperature variations (Sikder, 2009; Ram et al. 2012). The temperatures below 10 °C or above 25 °C particularly alter the phenology, growth, and development, and therefore the yield of wheat (Porter and Gawith 1999; Hakim et al. 2012). However, temperatures above 35 °C (± 0.5) could be catastrophic for wheat production (Porter and Gawith 1999). The ideal temperature required for wheat is ~10–15 °C during winter and ~21–26 °C during summer (Porter and Gawith 1999). A study by Wang et al. (2017) suggested that yield increase over the period from 1980 to 2001 C.E. was mostly due to cooling trends in night temperatures benefiting plant growth (Wang et al. 2017). The study estimated increased winter wheat yield in Eastern Australia, benefiting from warming-induced early flowering even without cultivar adjustment (Wang et al. 2017). However, beyond a certain point, higher

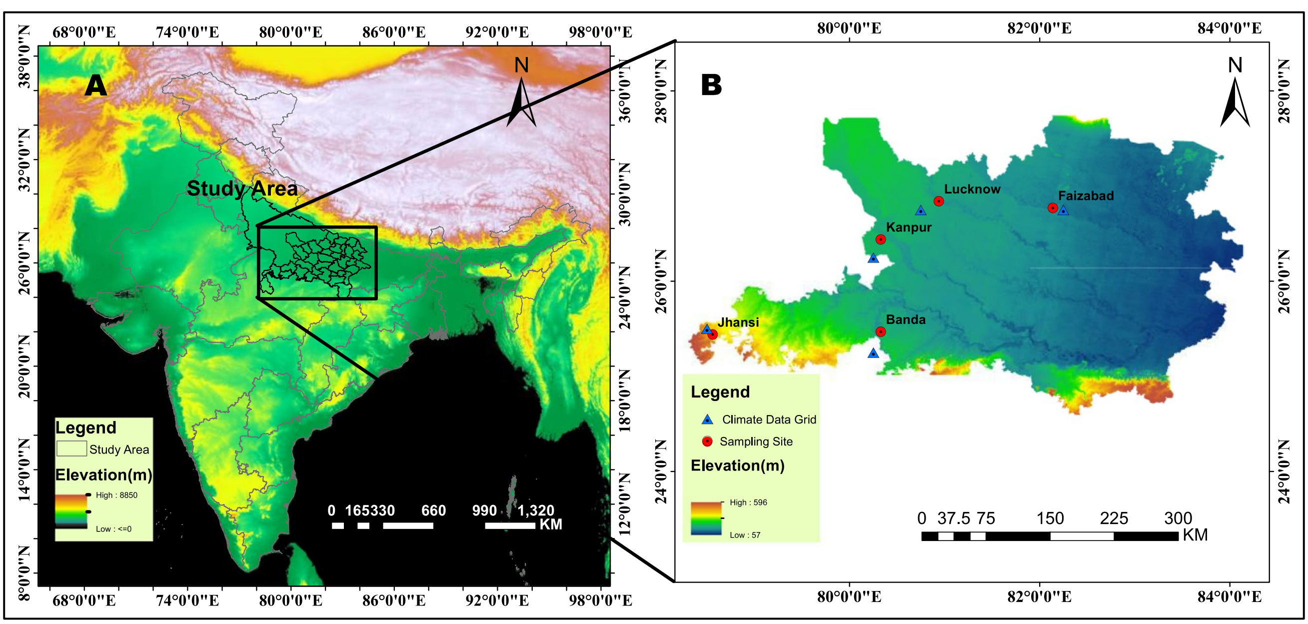


**Fig. 1** Map showing locations of wheat yield sites and climate grid points using ASTER Global Digital Elevation Model (ASTGTM), 30-m resolution data (https://gdex.cr.usgs.gov/gdex/) for **A** general view of study area and **B** location of wheat yield and climate grid sites. The red circles are the wheat yield, and the blue triangles are climate grid sites, i.e. CRU TS.4.03 temperature (mean, maximum, and minimum), Precipitation, Palmer Drought Severity Index (PDSI) and Standardized Precipitation-Evapotranspiration Index (SPEI) grid point, respectively

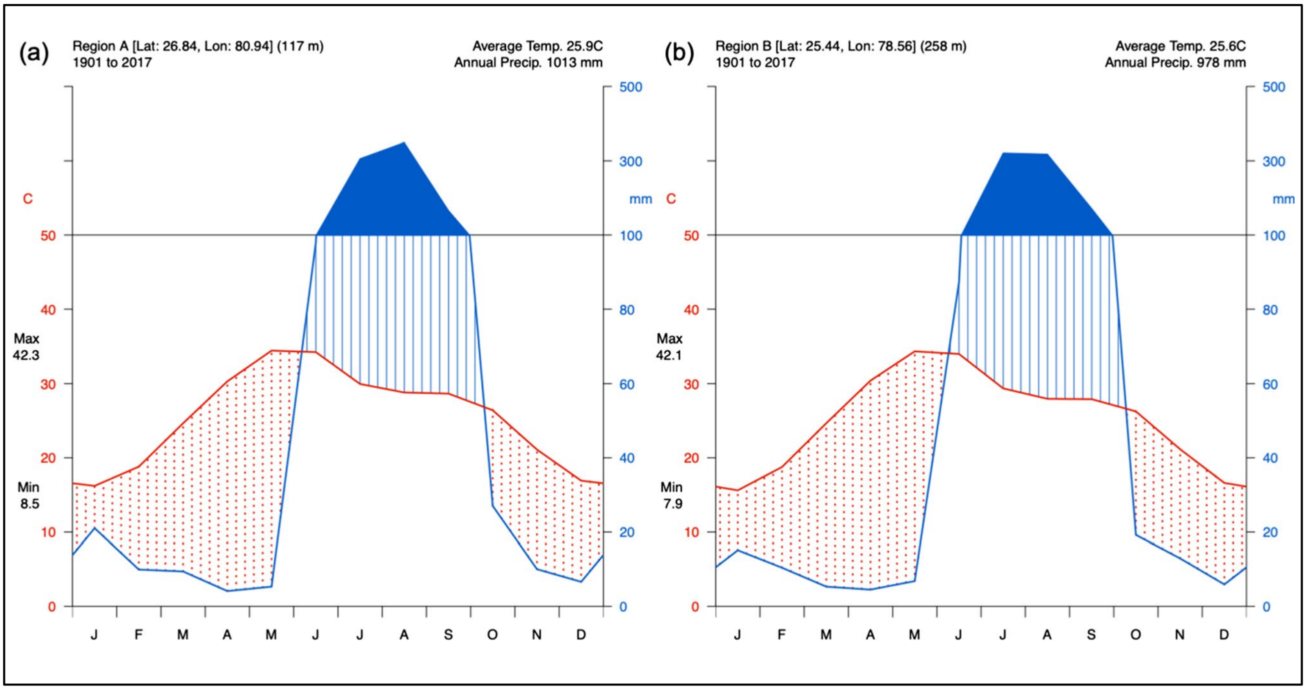


**Fig. 2** Walter and Leith climate diagram of (**a**) Region A (Lucknow, Kanpur, Faizabad, Banda) and (**b**) Region B (Jhansi) regional climate used for nearest grid points of Climate Research Unit's TS 4.03. Blue line represents precipitation curve and red line represents temperature curve. Values on the left axis are average maximum temperature of the warmest month and average minimum temperature of the coldest month. Upper right corner of the diagram shows annual average of temperature and annual total precipitation. The period for different grid point is 1901–2017C.E

air temperatures adversely affect plant growth, pollination, and reproductive processes (Sacks and Kucharik, 2011). Another study used a statistical approach to estimate wheat, corn, and cotton yield declines of 36 to 40% under a low $CO_2$ emissions scenario and between 63 to 70% for high $CO_2$ emission scenarios (Attri and Tyagi, 2010).

## 2.3 Climate data

The study area comprises of five districts of UP which fall broadly under a tropical monsoon type of climate (Attri and Tyagi, 2010). Data from the meteorological stations are often not the true representative of the entire study sites as the long-term meteorological stations in this region are very few; the data for recent years is often not available in public domain and the stations can be very far from the district centres. To overcome this data insufficiency, past climate data was acquired from three different sources for 1901–2017 C.E. and the common period for 1971–2011. The years 1971 to 2011 C.E., were selected as the common period to establish the relationship between wheat yield and climate parameters. Since this period is more than 30 years, it is sufficient to allow climatological analysis and inferences detection (WMO, 1989; Guttman, 1989). The gridded monthly climate data, which are mean temperature (Tmean), maximum temperature (Tmax), minimum temperature (Tmin), and total precipitation, are acquired from the Climate Research Unit, University of East Anglia, UK, with a 0.5° (~50 km) spatial resolution (Fig. 2). The details of the gridded data and source stations are shown in Fig. 1. In the present study, the globally gridded PDSI and SPEI dataset with 0.5° spatial resolution at 12-month time scale (Palmer, 1965; Vicente-Serrano et al. 2010) are used for the period 1971 to 2011 C.E. in the nearest gridded dataset. The SPEI values range from – 5 to 5 in which the lower or negative values show a stronger degree of drought, and the higher values indicate a higher degree of moisture (Vicente-Serrano et al. 2013).

## 2.4 Statistical analysis

Several non-climatic factors influence wheat yield trends including changes in crop varieties, use of better technology, soil type, and quality and intensity of used fertilizers, manure, and pesticides. Therefore, the trend of change in the annual yield needs to be understood using both the parametric and nonparametric statistical methods. In the present study, we presumed that the climatic factors have more influence in the annual yield of wheat in comparison to the non-climatic factors. Primarily, the Bootstrap Correlation analysis was used to understand the wheat yield and climate relationship. The bootstrapping method explains the simulation of the sample distribution around a statistic parameter (mean, variance, and correlation coefficient) through the creation of multiple samples (usually thousands or tens of thousands of runs) with replacement (Efron 1979, 1982; Tibshirani and Efron, 1993). We also used linear regression to understand the variability trend of annual yield (Fig. 3a). We analysed the trend and magnitude of wheat yield as well as climate using the Mann–Kendall (MK) non-parametric test (Mann 1945), to assess the statistical significance of the trend. The positive values indicate an increasing trend and negative values indicate a decreasing trend, whereas zero value indicates no trend. The Mann-Kendal trend tests were performed using package "Kendall" (McLeod, 2005) in the R programming environment Version 3.5.1 (R Core Team, 2018). Further, the possible role of mean, maximum and minimum temperature, precipitation, SPEI, and PDSI of specific month or season on yield was analysed using the correlation coefficient. The confidence intervals of correlations were between 95 and 99% (Supplementary Table 2). We considered the period between August and following year May month to analyse the relationship between climate variables and wheat yield. For correlation analyses, we included monthly data of rainfall, and temperature, covering the period from August to December and January to May in the consecutive year.

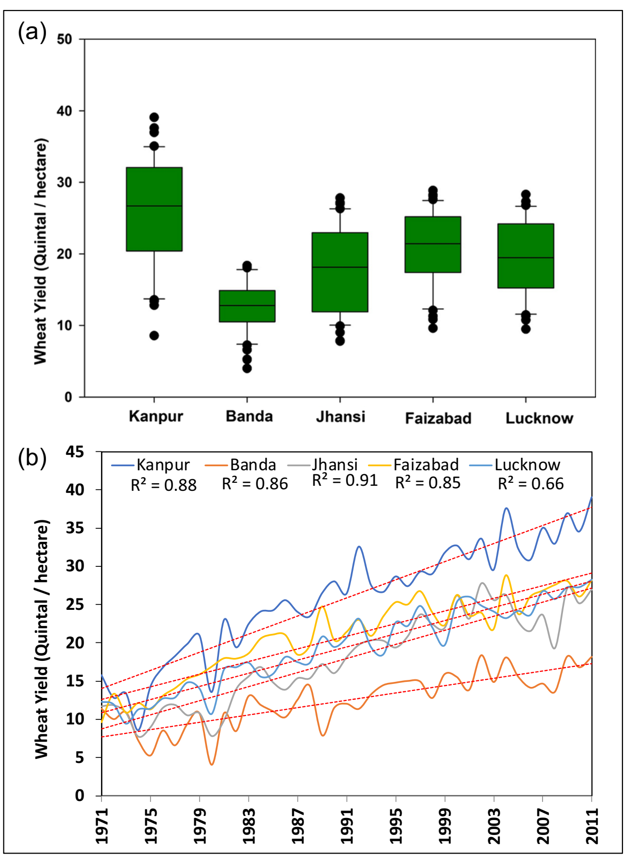


**Fig. 3** (**a**)The box plot graph showing the wheat yields variability in UP (1971–2011C.E.) and (**b**) the linear regression plot of wheat yield

To further investigate the most influential climatic parameters for wheat yield, we used the redundancy analysis (RDA), which is a method to extract and summarize the variation in a set of response variables that can be explained by a set of explanatory variables (Legendre and Legendre, 2012). More accurately, RDA is a direct gradient analysis technique which summarizes linear relationships between components of response variables that are redundant with a set of explanatory variables. The RDA approach generates one ordination in the space defined by the matrix of response variables and another in the space defined by the matrix of explanatory variables. Residuals generated by the multiple linear regression steps, which yield non-canonical axes, may also be ordinated (Legendre and Legendre, 2012). Furthermore, the variance inflation factor (VIF), a statistical characteristic used to assess linear dependencies and detect multicollinearity in RDA analysis, was used. The VIF estimates the magnitude of the variance of a regression coefficient which is inflated due to multicollinearity in the model. The VIFs of 10 have been used as rules of thumb to indicate excessive or serious multicollinearity on the variance of regression coefficients (Belsley et al. 2005; O'brien, 2007). In the present study, we selected only those attributes showing VIFs less than 10 (O'brien, 2007). The other climatic attributes were removed using the stepwise method. The Monte Carlo permutation test was also used to reveal the effect of the obtained explanatory climatic variables on the wheat yield. A total of 499 permutations were performed, and results of the analyses were visualized in the form of ordination diagrams in the CanoDraw for Windows program (Ter Braak and Smilauer, 2002). Here the RDA was performed using Canoco 5.0 software (Microcomputer Power, Ithaca, NY, USA) to determine the most significant climatic variables influencing the yield. Lastly, to assess the influences of large-scale atmospheric circulation, and climate variations on the wheat production in this region, spatial correlation was made with temperature, precipitation (CRU TS.403), PDSI (Palmer), and global sea-surface temperatures (SSTs) from the HadISST1 dataset (Rayner et al. 2003) using the Royal Netherlands Meteorological Institute (KNMI) Climate Explorer (http://climexp.knmi.nl/) (Van Oldenborgh and Burgers 2005).

## 3 Results and discussion

### 3.1 Characteristics of yield vs. climate

The annual wheat yield of all the five districts is highly correlated with each other at 99% confidence level for the period 1971 to 2011 C.E. (Supplementary Table 2).

The analysis of annual yield of these five districts of UP shows mean (± standard deviation) as 25.87 (± 7.54), 12.47 (± 3.52), 17.95 (± 5.98), 20.86 (± 5.32), and 19.46 (± 5.38) Quintal/ha for Kanpur, Banda, Jhansi, Faizabad, and Lucknow, respectively (Table 1, Fig. 3a). The highest and lowest ever yields recorded for these districts were 39.08 and 4.02 Quintal/ha in the years 2010–2011 and 1979–1980 for Kanpur and Banda, respectively. The significant increase in wheat yield is observed for all districts with the value of Kendall's *tau* (τ) 0.839, 0.643, 0.746, 0.795, and 0.819 for Kanpur, Banda, Jhansi, Faizabad, and Lucknow, respectively (Table 2, Fig. 3b). However, the Region B remains a low agriculture productivity zone compared to other districts of UP and therefore comparatively a socioeconomically backward region which is mainly associated with the geology of the region (Singh and Shukla 2010). The overall analysis carried out for all five districts with climatic variables shows that the low yields are associated with low winter temperatures, whereas the high yields are associated with higher winter temperatures (Fig. 4). This is on the contrary to the analysis done in Nepal and the USA where the wheat yield is negatively correlated with mean monthly temperature (Bhatt et al. 2014; Tack et al. 2015), but this could be associated with breed of wheat being used and the elevation.

Temperature is a crucial factor affecting the rate of plant development especially because each species has a specific temperature range for their augmented development (Hatfield and Prueger, 2015). The influence of climatic factors in a particular month or season on the yield was identified by computing correlation functions. The confidence intervals of correlations being at 95% and 99% CL (Fig. 5). In the RDA analysis, the climatic attributes were selected based on the variation inflation factors (VIFs) (O'brien, 2007). The VIFs for the PDSI_N, PDSI_D, SPEI_N, and SPEI_D were more than 200 (Table 3). RDA results revealed that the first axis (RDA Axis 1) and the second axis (RDA Axis 2) of the climatic factors could explain 35.0% and 1.6% of the variations, respectively in the wheat yield for Jhansi, Banda, Kanpur, Lucknow, and Faizabad (Table 3; Fig. 6a). The RDA analysis also suggests that the previous year's average temperature of December is the most influencing factor for yield in the study area. Further, the yield and climate relationship for the time period of 2000 to 2011 C.E. also suggest that the winter months have a strong correlation for all the five districts, while the RDA results revealed that the first axis (RDA Axis 1) and the second axis (RDA Axis 2) of the climatic factors could explain 24.0% and 17.5% of the variations, respectively, in the wheat yield for Jhansi, Banda, Kanpur, Lucknow, and Faizabad (Table 4; Fig. 6b). The trend in temperature and rainfall (CRU TS.4.03), PDSI, and SPEI (Vicente-Serrano et al. 2010; 2013) is estimated by the non-parametric MK test, the results of which are presented in Table 4. The MK (*τ*) test for trend analysis was carried out for the climatic Regions A and B. The results showed the *τ* of MAT (τTmean) was 0.484 and 0.415 and the winter (τ) was 0.395 and 0.360 whereas the MAP (precipitation) − 0.241 and − 0.149, Monsoon (precipitation) − 0.205 and − 0.122, Winter (precipitation) − 0.200 and − 0.122, and PDSI (Winter) − 0.366 and − 0.170 for regions A and B, respectively (Table 4). The overall trends thus show that the temperature is increasing, while precipitation and moisture are decreasing in both regions. The moisture index (SPEI, PDSI) for winter is presented in Fig. 3 for different districts. The time series analysis shows that temperature, precipitation, and the moisture fluctuated year-to-year, but they reduced to low levels during the 2000–2010 C.E. period, particularly in Kanpur and Banda regions.

**Table 1** Details of different statistical parameters of wheat yield (1971–2011C.E.) for Uttar Pradesh

| Statistical parameters | Kanpur | Banda | Jhansi | Faizabad | Lucknow |
|---|---|---|---|---|---|
| Number of observations | 41 | 41 | 41 | 41 | 41 |
| Mean | 25.88 | 12.47 | 17.95 | 20.87 | 19.46 |
| Standard error | 1.18 | 0.55 | 0.93 | 0.83 | 0.84 |
| Standard deviation | 7.54 | 3.53 | 5.98 | 5.32 | 5.38 |
| Minimum | 8.55 | 4.01 | 7.78 | 9.59 | 9.47 |
| Maximum | 39.08 | 18.36 | 27.80 | 28.84 | 28.28 |
| Range | 30.53 | 14.35 | 20.02 | 19.25 | 18.81 |
| 1st quartile | 20.96 | 10.73 | 11.92 | 17.92 | 15.61 |
| Median | 26.67 | 12.76 | 18.13 | 21.42 | 19.48 |
| 3rd quartile | 31.79 | 14.85 | 22.79 | 25.02 | 24.12 |
| Sum | 1061.00 | 511.37 | 735.95 | 855.59 | 797.93 |
| Variance (*n*) | 55.49 | 12.12 | 34.90 | 27.63 | 28.24 |
| Variation coefficient | 0.29 | 0.28 | 0.33 | 0.25 | 0.27 |
| Kurtosis | − 0.53 | − 0.20 | − 1.20 | − 0.72 | − 1.14 |
| Skewness | − 0.41 | − 0.37 | − 0.03 | − 0.50 | − 0.16 |

**Table 2** Significant trend statistics (Mann–Kendall trend and Sen's slope) of wheat yield for all five districts of UP based on Mann–Kendall test

| Districts | Kendall's tau | *p*-value | Sen's slope |
|---|---|---|---|
| Kanpur | 0.83902 | $< 0.0001$ | 0.5718 |
| Banda | 0.64390 | $< 0.0001$ | 0.2348 |
| Jhansi | 0.74634 | $< 0.0001$ | 0.4687 |
| Faizabad | 0.79512 | $< 0.0001$ | 0.4220 |
| Lucknow | 0.81951 | $< 0.0001$ | 0.4278 |

### 3.2 Wheat crop management

The past climate data implies that the 2000s were warmer than the 1990s which were warmer than the 1980s, and so forth (Balmaseda et al. 2013; Held 2013; IPCC 2014). For the 30-year average, the rate of warming scaled from the

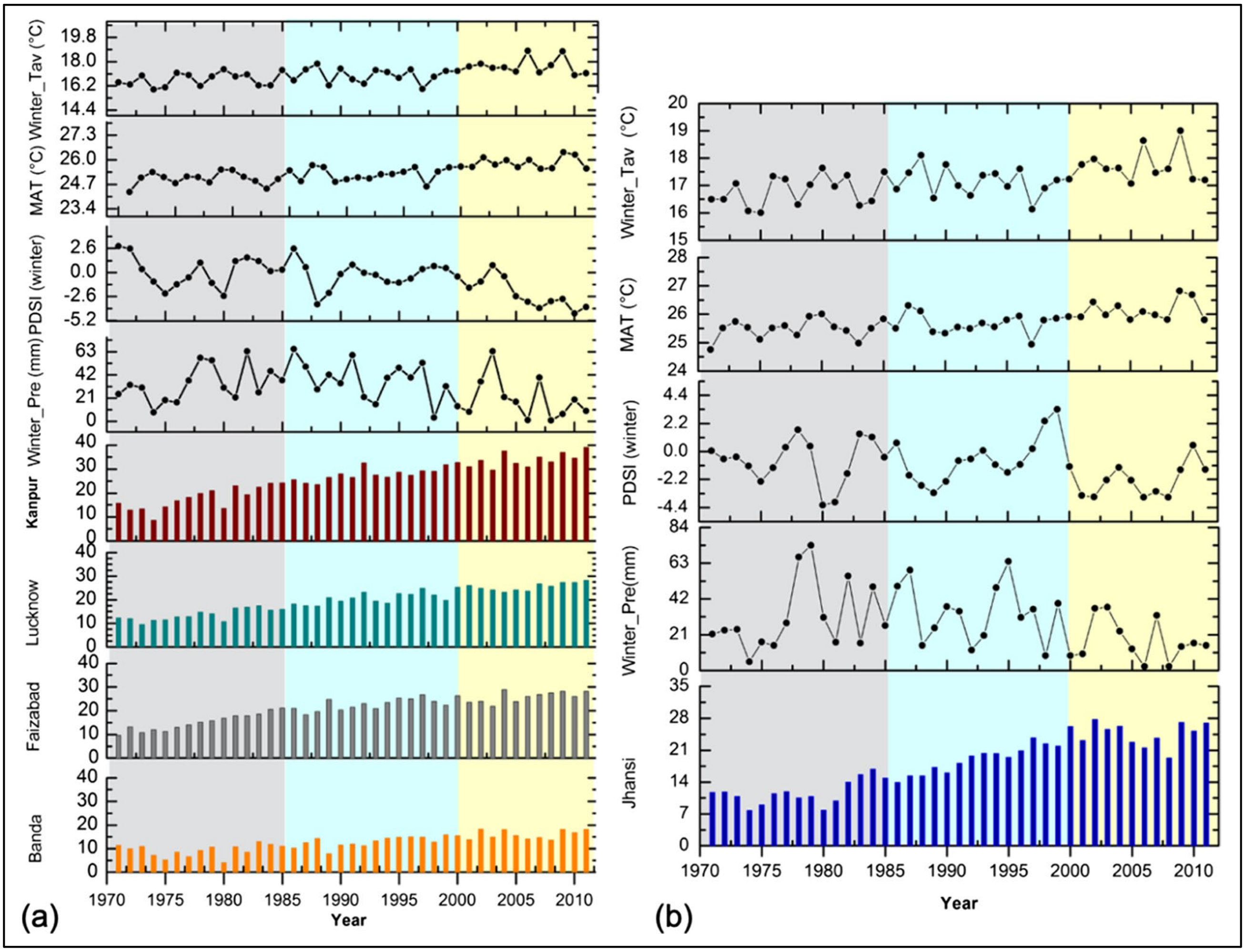


**Fig. 4** Composite diagram between yield and climate attributes namely winter temperature, mean annual temperature (MAT), PDSI (winter), and winter precipitation (mm) for (**a**) Region A including the districts Banda, Lucknow Faizabad, and Kanpur and (**b**) Region B including district Jhansi

1960s to around 2000 C.E. and has drifted over the past decade at a steady rate of around 0.16–0.18 °C per decade. This change in temperature is interestingly very close to the near-term warming projections in the IPCC of around 0.2 °C per decade (Supplementary Fig. 1). In this context, we analysed climate and yield data to understand the crop management aspect and role of climate. The result from the current analysis shows that the crop management aspect already reached its maximum limit of favouring annual yield of wheat by the year 2000 and thereafter the climate influence is observed. Although the moisture and rainfall are observed to be decreasing in the study area, there is a steady increase in the annual yield. The temperature is increasing with the same pace as yield, and it can be inferred that the increase in temperature is associated with the increase in yield and is influencing the wheat production in the Gangetic Plain in a positive feedback mechanism. The anomaly of average annual yield in UP shows that until 1990 the average annual was lower. The rise in annual yield of wheat production started after 1990 until 2000 C.E. mainly due to the use of different technologies and crop management practices. After 2000s, the increase in production can be attributed to the influence of winter temperatures (Supplementary Fig. 1). Moreover, short-term increases in wheat yield may reflect the positive effects of warming winter temperatures, but any global temperature increase (e.g., + 0.5 °C) is expected to have a negative impact on human health and crop productivity (Hoegh-Guldberg et al. 2018).

### 3.3 Yield/climate relationship and its teleconnections

One of the main objectives of the present study is to establish the statistical relationship between wheat yield and climate along with atmospheric circulation. It is essential to understand the wheat yield variability and its possible

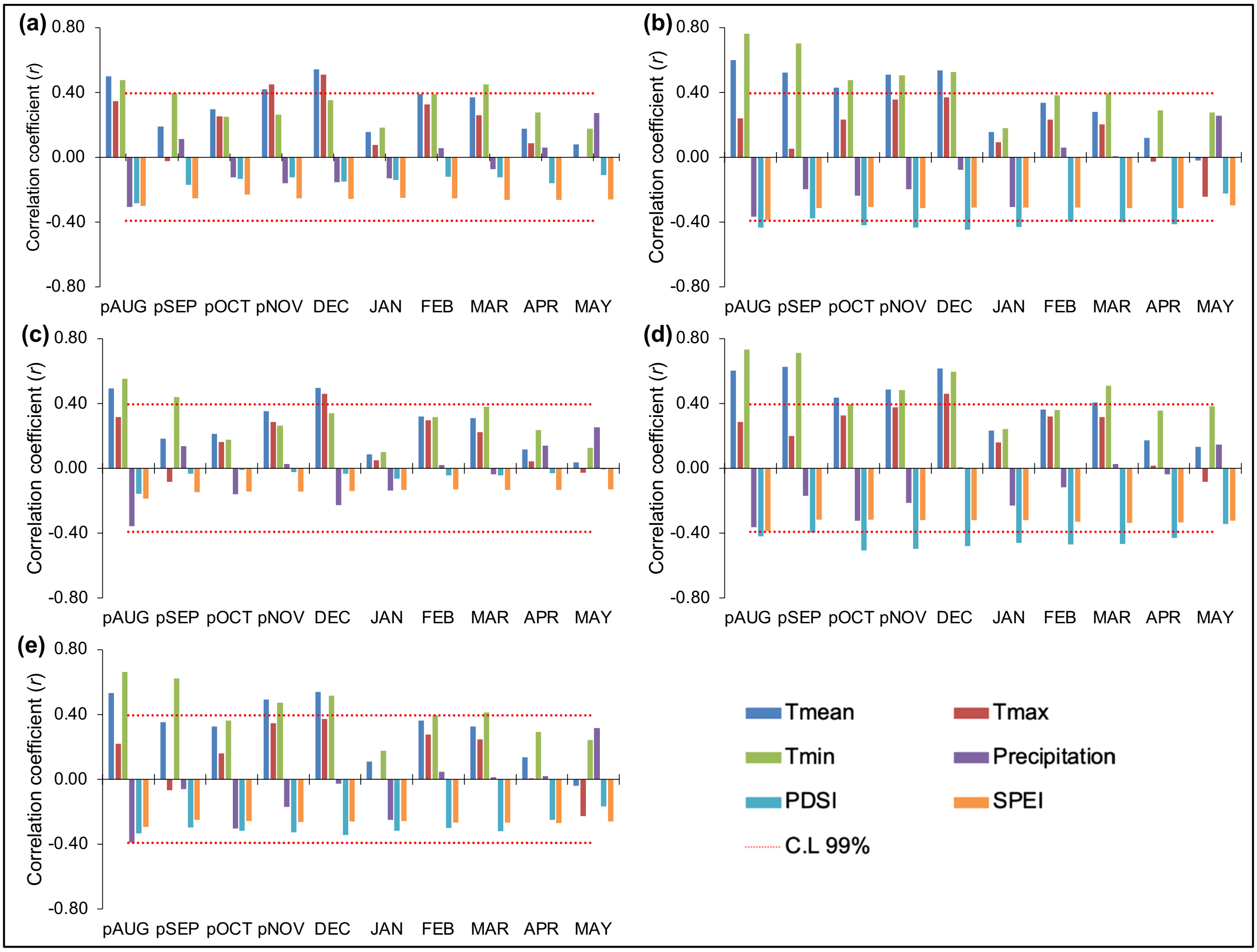


**Fig. 5** Correlation plot for wheat yield for (**a**) Banda, (**b**) Lucknow, (**c**) Jhansi, (**d**) Faizabad, and (**e**) Kanpur, with mean temperature (Tmean), maximum temperature (Tmax), minimum temperature (Tmin), precipitation, SPEI, and PDSI. The dotted horizontals lines indicate the 95% and 99% CL

**Table 3** The results of RDA analysis with an explanation of eigenvalues, yield climate correlation, and variance for the periods 1971–2011 and 2000–2011 C.E.

| Axis | 1 | 2 | 3 | 4 | Total variance |
|---|---|---|---|---|---|
| 1971–2011 C.E. | | | | | |
| Eigenvalues* | 0.350 | 0.016 | 0.003 | 0.001 | 1.000 |
| Yield climate correlations | 0.625 | 0.491 | 0.341 | 0.202 | |
| Cumulative percentage variance of yield data | 35.0 | 36.6 | 36.8 | 36.9 | |
| Cumulative percentage variance of yield – climate relation | 94.8 | 99.1 | 99.8 | 100.0 | |
| Sum of all eigenvalues | | | | | 1.000 |
| Sum of all canonical eigenvalues | | | | | 0.369 |
| 2000–2011 C.E. | | | | | |
| Eigenvalues* | 0.240 | 0.175 | 0.061 | 0.013 | 1.000 |
| Yield climate correlations | 0.708 | 0.764 | 0.580 | 0.675 | |
| Cumulative percentage variance of yield data | 24.0 | 41.5 | 47.6 | 49.0 | |
| Cumulative percentage variance of yield – climate relation | 48.8 | 84.4 | 96.8 | 99.5 | |
| Sum of all eigenvalues | | | | | 1.000 |
| Sum of all canonical eigenvalues | | | | | 0.492 |

*All four eigenvalues reported above are canonical and correspond to axes that are constrained by the climatic variables

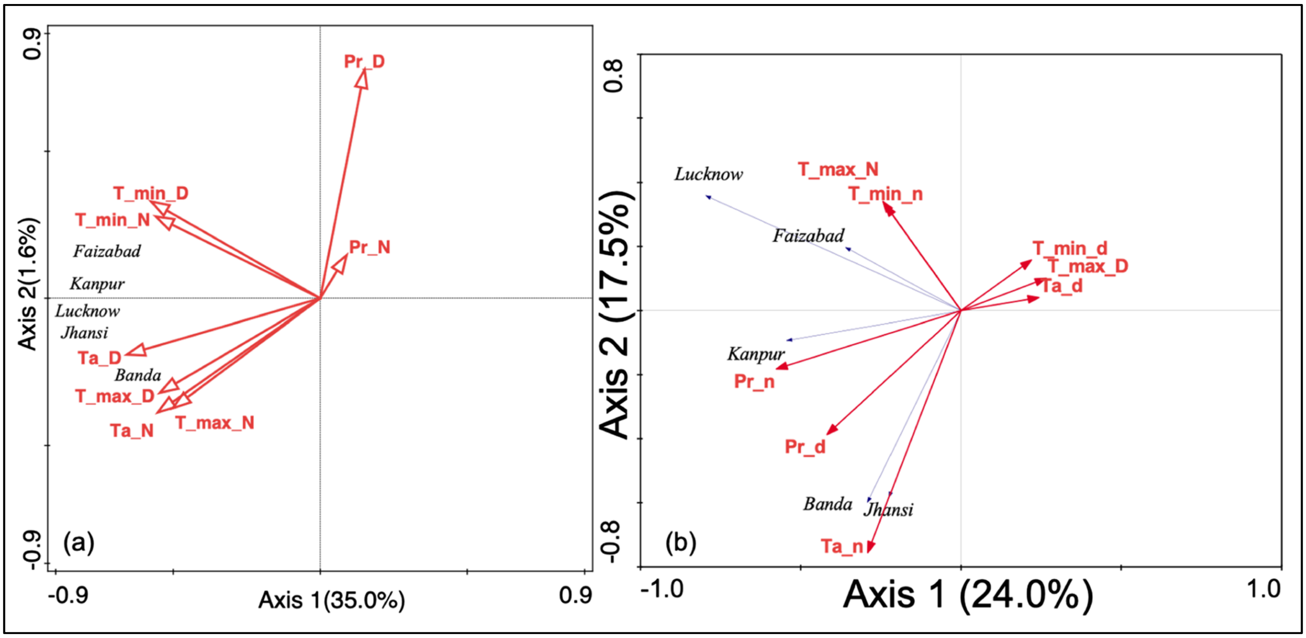


**Fig. 6** The RDA analysis showing the relationships between environmental factors and wheat yield. Time span covering the (**a**) 1971–2011 C.E. and (**b**) 2000–2011 C.E. [Climatic factors abbreviations: Ta_N, Ta_D, Tmax_N, Tmax_D, _Tmin_N, and Tmin_D are the previous year average temperature for November (Ta_N) and December (Ta_D); maximum temperature of November (Tmax_N) and December (Tmax_D); and minimum temperature of November (Tmin_N) and December (Tmin_D)

**Table 4** Significant trend statistics (Mann–Kendall trend and Sen's slope) for gridded climate points which are Region A and Region B for all five districts of UP based on Mann–Kendall test

| Climatic parameters | Kendall's tau | *p*-value | Sen's slope |
|---|---|---|---|
| Region A | | | |
| MAP | −0.241 | 0.027 | −7.618 |
| Monsoon (precipitation) | −0.205 | 0.061 | −6.507 |
| Winter (precipitation) | −0.200 | 0.067 | −0.604 |
| MAT | **0.484** | **<0.0001** | 0.024 |
| Winter (Tav) | **0.395** | **0.000** | 0.029 |
| PDSI (winter) | −0.366 | **0.001** | −0.246 |
| Region B | | | |
| MAP | −0.149 | 0.174 | −3.631 |
| Monsoon (precipitation) | −0.122 | 0.266 | −3.039 |
| Winter (precipitation) | −0.122 | 0.266 | −3.039 |
| MAT | **0.415** | **0.000** | 0.021 |
| Winter (Tav) | **0.360** | **0.001** | 0.028 |
| PDSI (winter) | −0.170 | 0.121 | −0.037 |

*Tav* mean temperature, *MAP* mean annual precipitation, *MAT* mean annual temperature

climate forcing factors which influence the yield. Crop yield variability is strongly related to regional temperature and precipitation anomalies (Iizumi et al. 2014). Here, we use teleconnections between yield and various climatic indices to understand possible climate forcing factors or driving factor that directly or indirectly influence the yield in UP in a regional and global perspective. The teleconnections were established with temperature, precipitation, and SST using correlation analysis. The highest correlation coefficients ($r=0.95$; $n=115$, $p\leq0.01$) between yield and temperature were observed in UP and the adjoining region. This approach is compromised by corrections of altitude and latitude and bias temperature data and associated lapse rate calculations. The analysis also does not confirm winter temperature as a dominant factor in modulating wheat production throughout the world, despite positive correlations in many parts of the world. Therefore, the objective of this analysis was to understand the statistical relationship of annual yield with increasing winter temperatures.

Moreover, the relationship shows the linkage and influence of mean temperature and SST on the annual yield of wheat (Fig. 7). These maps were created by establishing a correlation between yield and climate data, with special attention to ascertain the influencing factor on yield. A significant positive correlation of the annual yield with November and December temperatures was recorded whereas a negative correlation with PDSI and SPEI was observed (Supplementary Table 2). Further, the correlation of annual wheat yield was observed to be insignificantly negative with winter precipitation except for November in Jhansi and Faizabad. Annual yield of wheat in UP is also influenced by atmospheric circulation centred in the Pacific Ocean in terms of moisture availability evident by the significant positive correlation with SST of the Arabian Sea and the Pacific Ocean (Fig. 7). The annual mean SST is determined by the heat exchange between ocean and atmosphere. This relation could be explained as warmer SST temperatures, which are determined by the heat exchange between the ocean and atmosphere, which may indirectly affect the photosynthesis process of the crop. The photosynthesis constitutes the largest flux of $CO_2$ between the atmosphere and the Earth's surface (Stocker et al. 2013). The photosynthetic temperature acclimation processes are observed to increase carbon uptake and storage on land in the future (Lombardozzi et al. 2015). The negative relationship of wheat with precipitation during these winter months might be due to the excess wetting of soil leading to damage of saplings of the crop. We also find a positive relationship with winter temperature and negative with precipitation during these months in the adjoining areas of India (Fig. 8a, b). When the increase in temperature and rainfall reaches its threshold value for augmenting the growth of a crop, the phenology of the crop including photosynthesis, growth, absorption rate, water, and nutrient distribution get affected at the regional level (Long, 1991; Porter and Gawith 1999). Further, at higher temperature, the development of wheat is linked with an acceleration of the maturity of grain (FERRIS et al. 1998; Wheeler et al. 2000). The optimum temperature for maximum dry matter accumulation and the high night temperature is required for the growth of shoot (Acevedo et al. 2002). Besides, the foggy days during the early growth stages of the wheat crop (Joshi et al. 2007) and the seasonal variation in weather parameters could also influence pest and disease infestation to limit the yield (Aggarwal, 2008a, b). In another study for Punjab and Haryana, wheat yield did not show significant correlation with winter and monsoon precipitation, which indicates an indirect relationship (Mukherjee et al. 2019). The positive and significant correlation with winter temperatures show that higher winter temperatures accelerate plant growth. On the contrary, higher temperature in the late growth stage of wheat crop causes heat stress (temperatures above 32 °C) as anthesis can accelerate leaf senescence (Al-Khatib and Paulsen, 1984), and the grain filling period tends to be shorter, limiting time for grain growth (Asseng et al. 2011). Moreover, analysis suggests that low rainfall in November and December is considered to have had relatively little impact on potential yield. During the winter, when rainfall exceeds plant demand, the excess is effectively lost to crops and does not contribute to yield. Under rainfed circumstances water is accumulated in the soil profile prior to sowing and the stored water helps to maintain the crop early in the season, even when rainfall may be minimal during this period.

Conclusively, the winter temperature is a limiting factor that control the annual yield of wheat in the study area. The yield of a crop is controlled not by the total amount of resources available, but by the availability of the scarcest resource "the limiting factor". The concept was derived from observations that applying more of a nutrient that was not limiting did not improve crop yields. The concept of limiting factors has been used to explain the ecological phenomena (Fritts, 1978; Messier, 1991; Thomson et al. 1996; Rettie and Messier 2000; Shekhar, 2014; Shekhar and Bhattacharyya, 2015; Shekhar et al. 2022).

## 4 Conclusions

The change in climatic conditions will affect the agricultural production systems of the world. Therefore, research on understanding the impact of climate on yield production is vital. The present study explores the relationship between wheat yield and climate for UP, India, showing

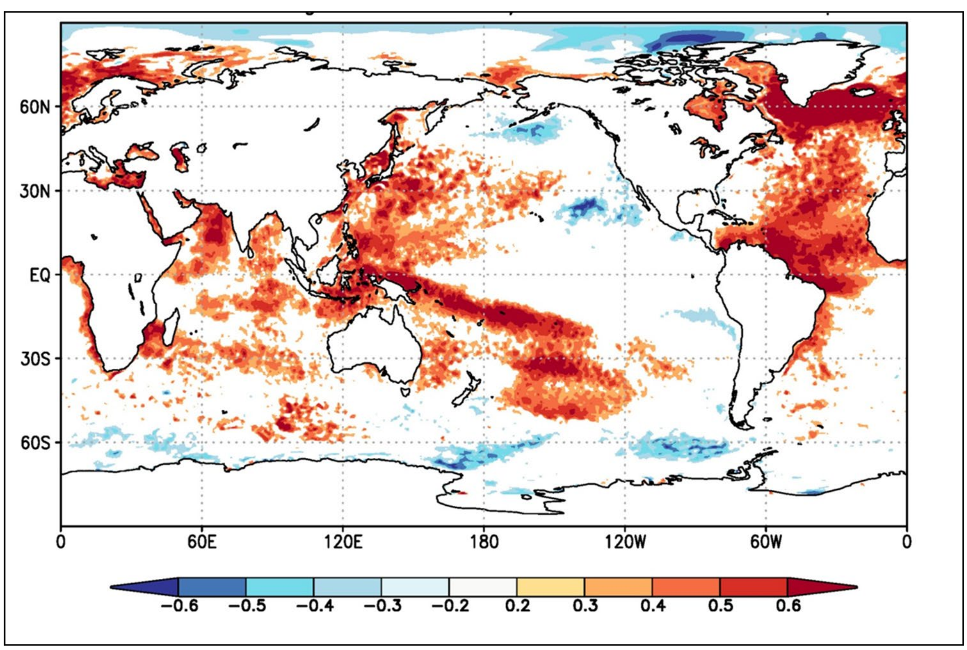


**Fig. 7** Spatial correlation between wheat yield and previous year's November–December sea surface temperature

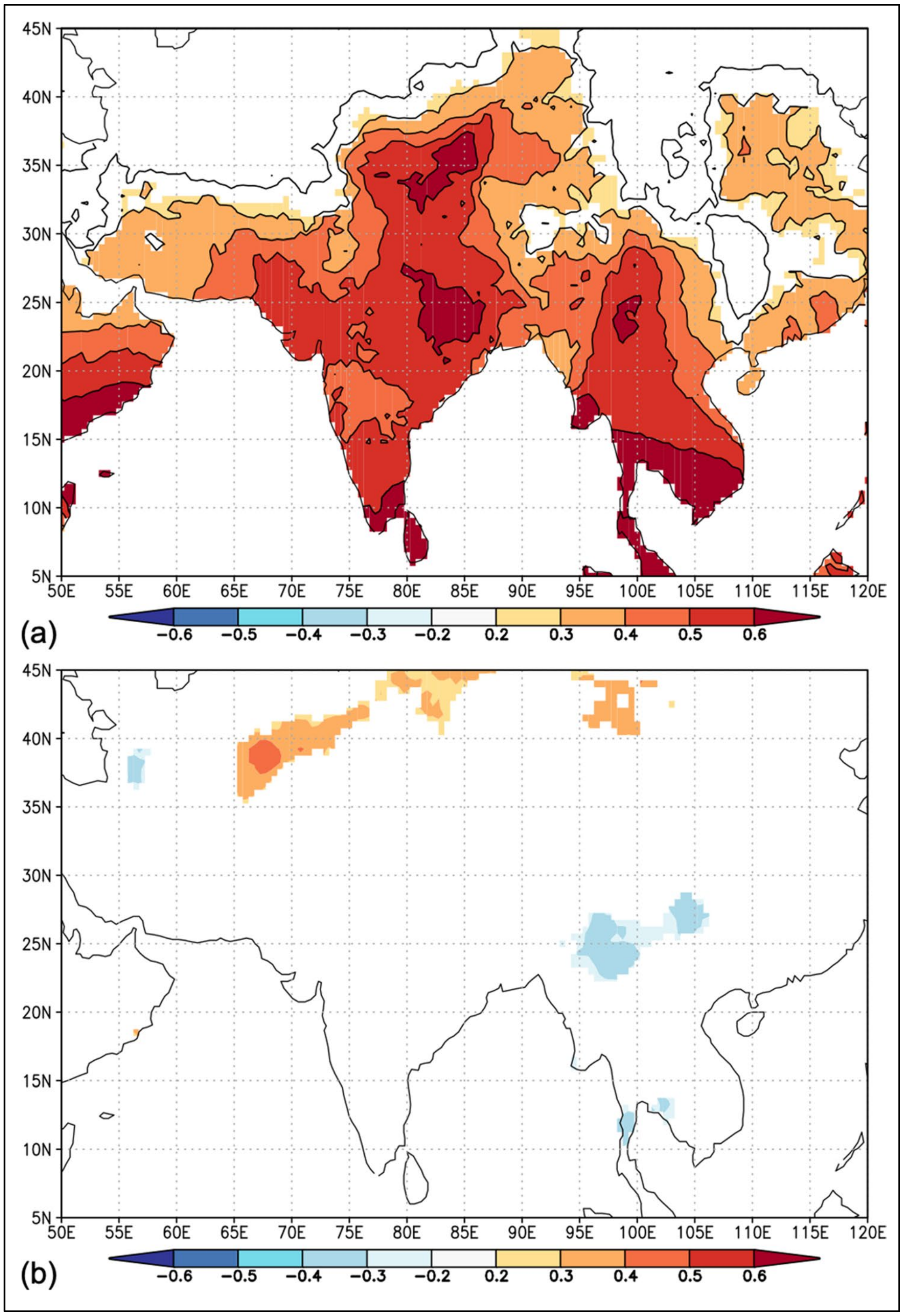


**Fig. 8** Spatial correlation between wheat yield and previous year November–December (**a**) temperature and (**b**) precipitation and PDSI in and around adjoining area of UP

for the first time that winter temperatures have a major impact on the growth of wheat crop in this region. In the present study, we address the effects of climate including moisture (PDSI, SPEI) and climate-yield relationship and their drivers. We also addressed the effects of climate change before and after 2000 C.E., focusing on physiological responses and adaptation. Our findings confirm a statistically significant link between wheat yield and winter temperature variability in UP during 1971–2011 C.E. These relationships could explain a closer linkage between wheat yields and winter climate. The analysis reveals the highest yield in the Kanpur district (39.08 Quintal/ha) during 2010–2011 C.E. and lowest in the Banda district (4.02 Quintal/ha) during 1979–1980 C.E. The RDA results further strengthen the correlation with winter months, especially with December mean temperatures. The yield reveals several high and low years since 1971 C.E. Moreover, the yield responded statistically significant linear relationship with temperature rise for the years 1971–2011 C.E. in all the study areas. We observed that pre-summer temperatures of UP range below the threshold limit of temperature requirement for maximum yield, limiting the annual yield. The low yield of wheat is related to low precipitation and PDSI, SPEI values in the winter months. The results demonstrate that there is a need for further investigation of experimental data to constrain temperature-driven processes in regional-scale crop models. The multi-location trial data are required and need to be incorporated in crop models to capture the full range of genetic variation of crops and their interaction with the environment. Moreover, the temporal wheat production in UP and its linkage with winter warming is universal and regional- or a site-specific response, needs to be addressed in the future. Climate change can open a new window of discussion in the development of high-yielding wheat varieties, but the wheat yield production is a complex process of interaction with climate and other variables which are not one to one relationship. Besides, adoption of high-yield variety, using fertilizers, undoubtedly enhanced the yield of wheat, but our study reveals that despite all these advancements, winter temperature plays a significant role to limit the yield of this Rabi crop.

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s00704-022-04246-7.

**Acknowledgements** We express our gratitude to Dr. (Mrs.) Vandana Prasad, Director, BSIP, for providing official permission to publish (vide: BSIP/RDCC/Publication no.23/2019-2020) and necessary facilities to carry out this work. PSR and MS acknowledge the in-house Project-8 of Birbal Sahni Institute of Palaeosciences, Lucknow, Uttar Pradesh, India.

**Author contribution** MS, MUS, SS, and RD conceived the study and developed the method. MS wrote the first draft of the manuscript with support from SS and AB. MS, MUS, SS, AB, and RD contributed to data collection and conducted the analysis with support from LS. PSR and ALB provided overall supervision and contributed to the writing. All the authors edited the previous versions of the manuscript and approved the final manuscript.

**Data availability** Data are available from the corresponding author upon reasonable request.

**Code availability** Not applicable.

## Declarations

**Ethics approval** Not applicable.

**Consent to participate** Not applicable.

**Consent for publication** All the authors have consented to publish this study.

**Conflicts of interest** The authors declare no competing interests.

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