

Rising winter temperatures ~~favour~~ augments increasing wheat yield in Gangetic Plains

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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 these 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 also 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. Moreover, 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 in India indicating 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.

Keywords: Climate change, wheat yield, food security, Gangetic plains

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 2008; Change, I. C. 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 (Singh and Mustard 2012; Kumar et al. 2014). [4,5]. The annual wheat production in India is ~85.7 Mt 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 [6]. 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) (Directorate of Economic and Statistics Ministry of Agriculture and farmers Welfare, Govt of India <https://eands.dacnet.nic.in/>). 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 thousand kg/ha (Directorate of Economic and Statistics Ministry of Agriculture and farmers Welfare, Govt of India. <https://eands.dacnet.nic.in/>).

There have been several attempts to assess the yield of crops under different climate change scenarios (Lal et al. 1998; Kumar et al. 2012, 2014) [5,8–13]. 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 CO₂ fertilization-(Aggarwal 2008) . 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 (Change, I.C. 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; Rajeevan,et al. 2008; Change, I. C. 2014). 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, although the rate of yield increase accelerated significantly after the end of 1990s (Clay 2002)^[1]. 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 ~~1966–1967~~late 1960s, India adopted a new nationwide strategy, also known as the Green Revolution, which led to initiatives the Green revolution 1967–1968, 1970 such as introduction of semi dwarf wheat variety like Sonara 64, Lema Roja, Sonalika etc.^[21](Dalrymple 1974). In addition, this also led to during 1980 increased reliance on agricultural machinery (use of tractor) particularly in the states of UP, Punjab and Haryana ~~especially~~ 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 cultivated-ion area ~~under wheat~~ at national level has

~~shown a significantly increased~~ during 2008-2013, from 29.04 million ha to 30.54 million ha with ~~a magnitude of~~ 1.5 million ha (5%) net gain ~~in terms of area~~. 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%) [22]. 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](#))~~[22]~~. However, a major expansion in wheat sowing area was observed in the states such as Jharkhand (51%), Madhya Pradesh (27%) and Rajasthan (13%) (<https://icar.org.in/files/state-specific/chapter/120.htm>). Moreover, the increase in wheat yield were not uniform across the Indian states; the greatest increases were in U.P, M.P, Haryana and Punjab ([Joshi et al. 2007](#))~~[23]~~.

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 (Gol Farmers portal, 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](#))~~[24]~~, 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](#))~~[25]~~ and Palmer Drought Severity Index (PDSI) ([Palmer 1965](#))~~[26]~~ 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 (Figure 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 (https://eands.dacnet.nic.in/https://eands.dacnet.nic.in/latest_20011.htm). The five districts which we have selected for the present study sample are the largest contributors of wheat production in UP (Agriculture statistic at a glance 2014–2015; https://eands.dacnet.nic.in/https://eands.dacnet.nic.in/latest_20011.htm). 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) (<https://icar.org.in/files/state-specific/chapter/120.htm>). 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, to be and 25.6 °C, respectively. The temperature in Region A varies between 7.9°C and 42.1 °C while in Region B it varies between 8.5 °C and 42.3 °C (Figure 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 (Figure 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 ([http://idup.gov.in/Irrigation and Water Resource Department UP](http://idup.gov.in/Irrigation-and-Water-Resource-Department-UP)). 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 (Department of Agriculture Uttar Pradesh, (<http://upagripardarshi.gov.in/>)).

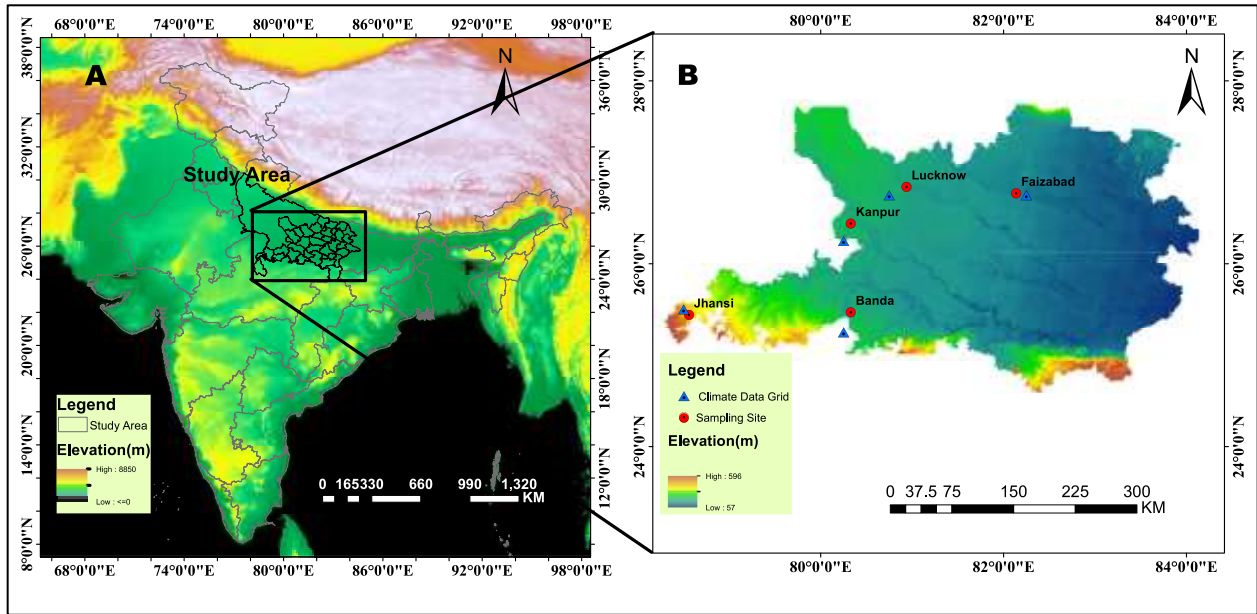


Figure 1: Map showing locations of wheat yield sites and climate grid points using ASTER Global Digital Elevation Model (ASTGTM), 30 m resolution data (<https://gdex.cr.usgs.gov/gdex/>) for (a) General view of study area, (b) Location of wheat yield and climate grid sites. The red circles are the wheat yield, and the blue triangles are climate grid sites i.e., CRU TS.4.03 temperature (mean, maximum, and minimum), Precipitation and Palmer drought severity index (PDSI) and The Standardized Precipitation-Evapotranspiration Index (SPEI) grid point, respectively.

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 (Department of Agriculture Uttar Pradesh, (<http://upagripardarshi.gov.in/>)). In UP, wheat is usually sown during late October to November and is harvested from April to May depending on the seasonal weather condition

(<http://upagri.pardarshi.gov.in>). 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](#))^[27,28]. The temperatures below 10 °C or above 25 °C particularly alter the phenology, growth and development, and therefore the yield of wheat ([Porter 1999; Hakim et al. 2012](#))^[29,30]. However, temperatures above 35°C (± 0.5) could be catastrophic for wheat production ([Porter 1999](#))^[29]. The ideal temperature required for wheat is ~10-15°C during winter and ~ 21-26 °C during summer ([Porter 1999](#))^[29]. A study by [Wang et al. 2017](#)^[31] 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 [31]. The study estimated increased winter wheat yield in Eastern Australia, benefiting from warming-induced early flowering even without cultivar adjustment ([Wang et al. 2017](#))^[31]. However, beyond a certain point, higher air temperatures adversely affect plant growth, pollination, and reproductive processes (Sacks and Kucharik 2011).^[32] Another study used a statistical approach to estimate wheat, corn, and cotton yield declines of 36% to 40% under a low CO₂ emissions scenario, and between 63% to 70% for high CO₂ emission scenarios (Attri and Tyagi 2010)^[33].

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)^[33]. 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 also the common time period for 1971-2011. The years 1971 to 2011 C.E., were selected as the common time 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 (T_{mean}), maximum temperature (T_{max}), minimum temperature (T_{min}) and total precipitation, ~~(Pre)~~, are acquired from the Climate Research Unit, University of East Anglia, UK, with a 0.5 degrees (~50

km) spatial resolution [36] (Figure 2). The details of the gridded data and source stations are shown in Figure 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)[25,26] 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)[37].

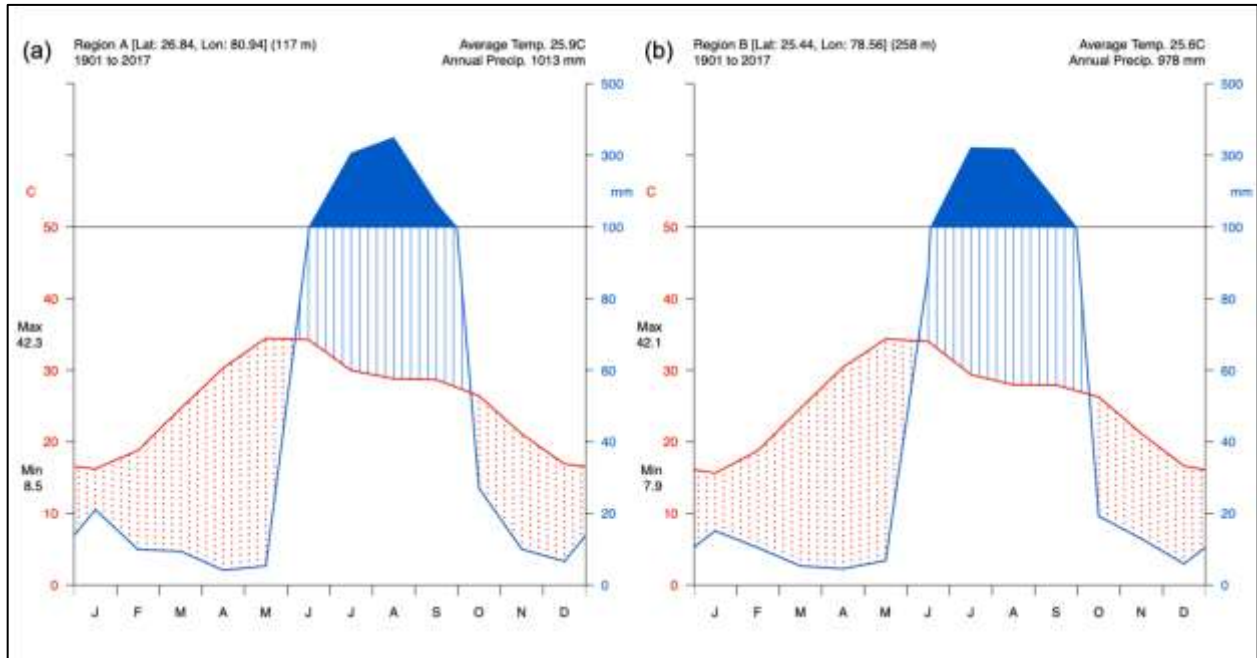
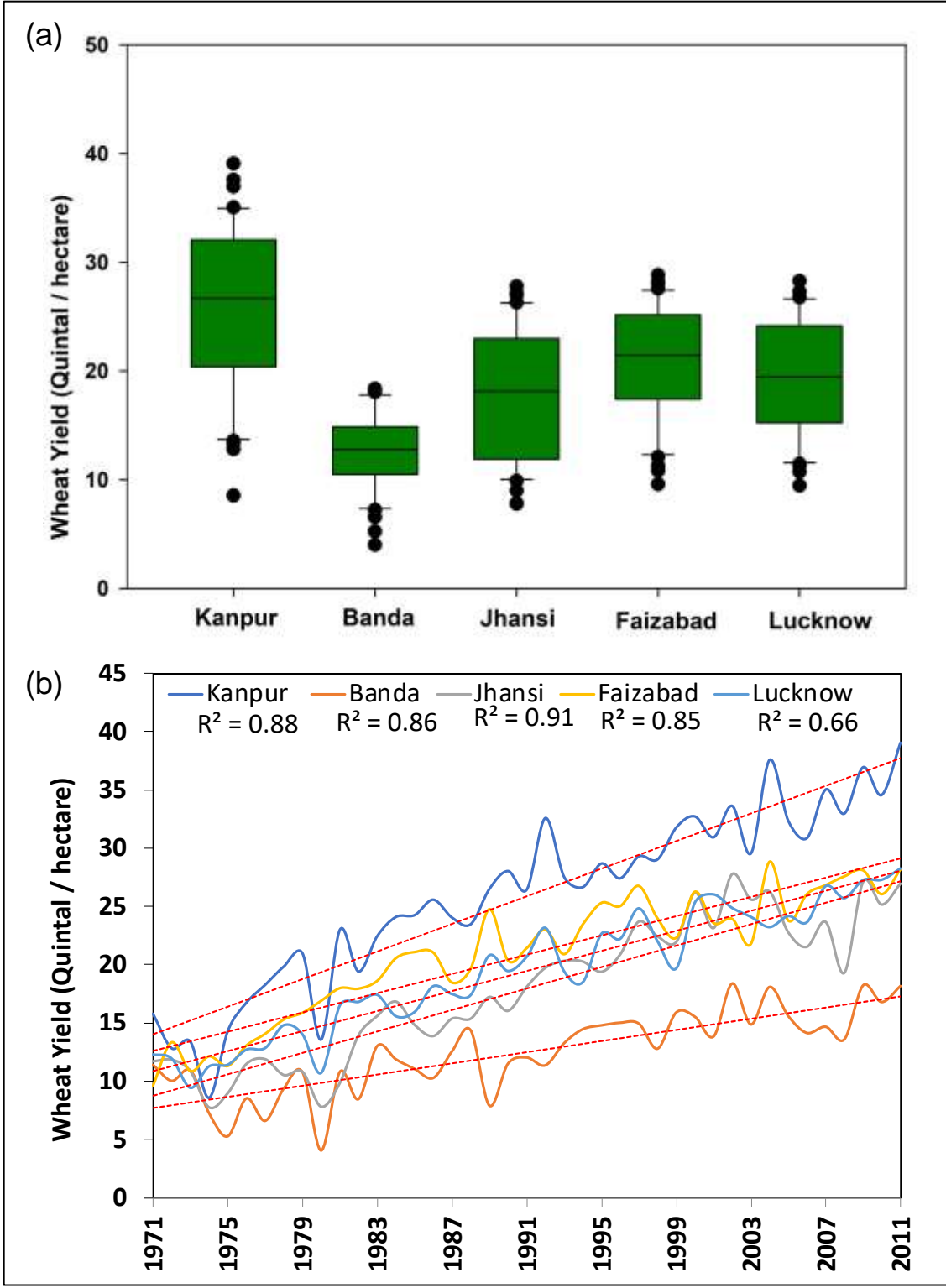


Figure 2: Walter and Leith climate diagram of (a) Region A (Lucknow, Kanpur, Faizabad, Banda and (b) Region B (Jhansi) regional climate used for nearest grid points of Climate Research Unit’s TS 4.03. Blue line represents precipitation curve and red line represents temperature curve. Values on the left 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 time period for different grid point is 1901–2017C.E.

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).[\[38–40\]](#). We also used linear regression to understand the variability trend of annual yield (Figure 3a). We analysed the trend and magnitude of wheat yield as well as climate using the Mann-Kendall (MK) non-parametric test (Mann 1945, 1975). 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)[\[44\]](#). Further, the possible role of mean, maximum and minimum temperature, preSPEI and PDSI of particular 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.



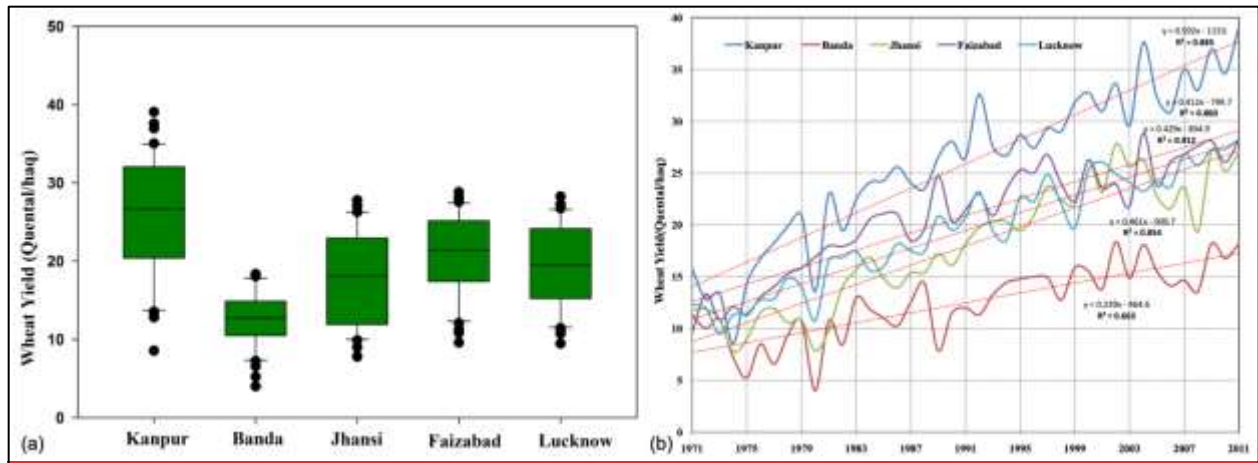


Figure 3: (a) The box plot graph showing the wheat yields variability in U.P (1971-2011C.E) and (b) The linear regression plot of wheat yield

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 [\(Legendre and Legendre 2012\)](#)[45]. 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 [\(Legendre and Legendre 2012\)](#)[45]. 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 [\(Belsley et al. 2005; O'brien 2007\)](#)[46,47]. In the present study, we selected only those attributes showing VIFs less than 10 [\(O'brien 2007\)](#)[47]. 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](#))[48]. 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 were made with temperature, precipitation (CRU TS.403), PDSI (Palmer) and global sea-surface temperatures (SSTs) from the HadISST1 dataset ([Rayner et al. 2003](#)) [49] using the Royal Netherlands Meteorological Institute (KNMI) Climate Explorer (<http://climexp.knmi.nl/>) ([Van Oldenborgh and Burgers 2005](#); [Trouet and Van Oldenborgh 2013](#))[50,51].

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 time period 1971 to 2011 C.E (Supplementary Table 2). The analysis of annual yield of these five districts of U.P shows mean (\pm standard deviation) as 25.87 (\pm 7.54), 12.47 (\pm 3.52), 17.95 (\pm 5.98), 20.86 (\pm 5.32), and 19.46 (\pm 5.38) Quintal/ha for Kanpur, Banda, Jhansi, Faizabad, and Lucknow, respectively (Table 1, Figure 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, 0.819 for Kanpur, Banda, Jhansi, Faizabad, and Lucknow respectively (Table 2, Figure 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 (Figure 4). This is on the contrary to the analysis done in Nepal and the United States of America 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.

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 U.P 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

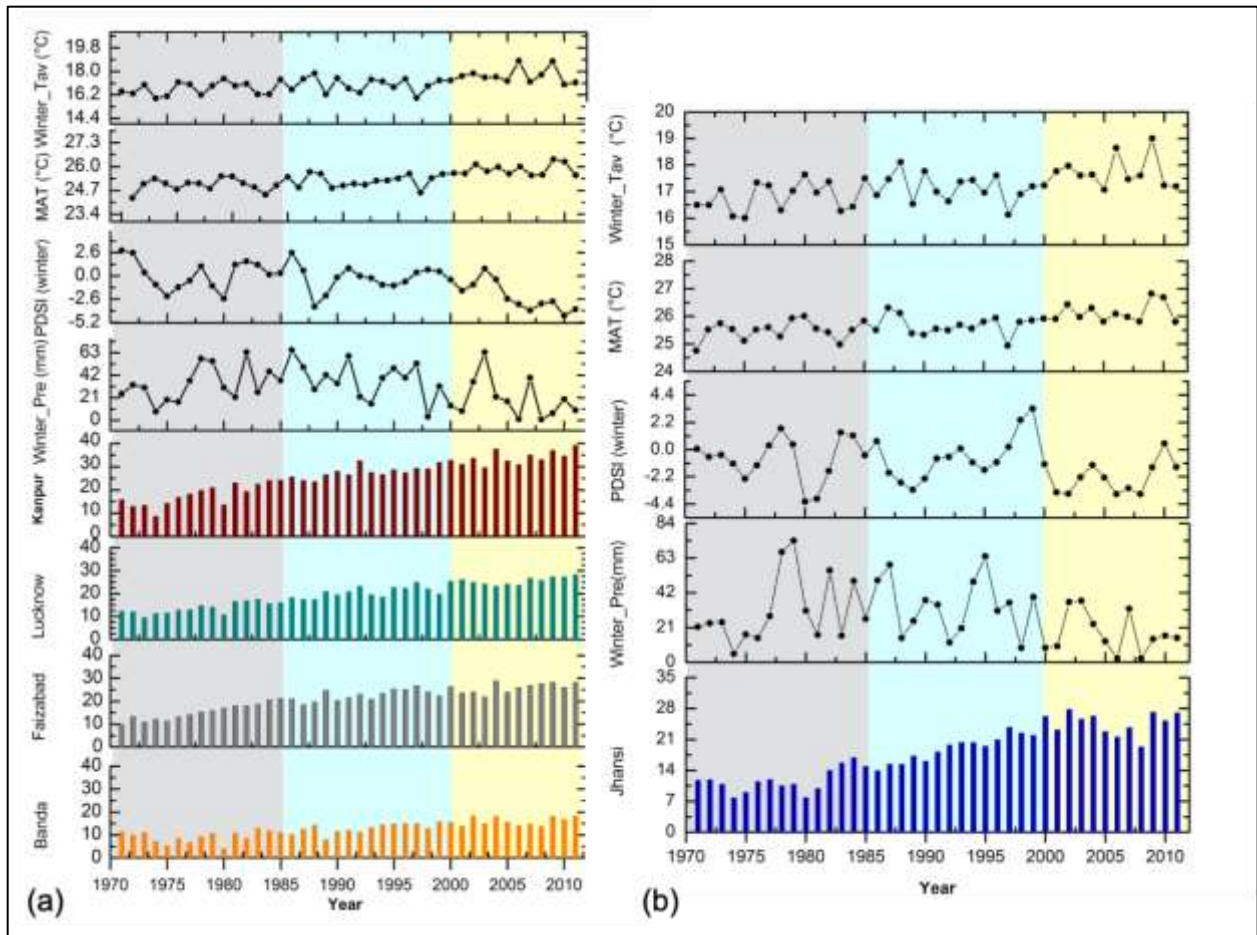
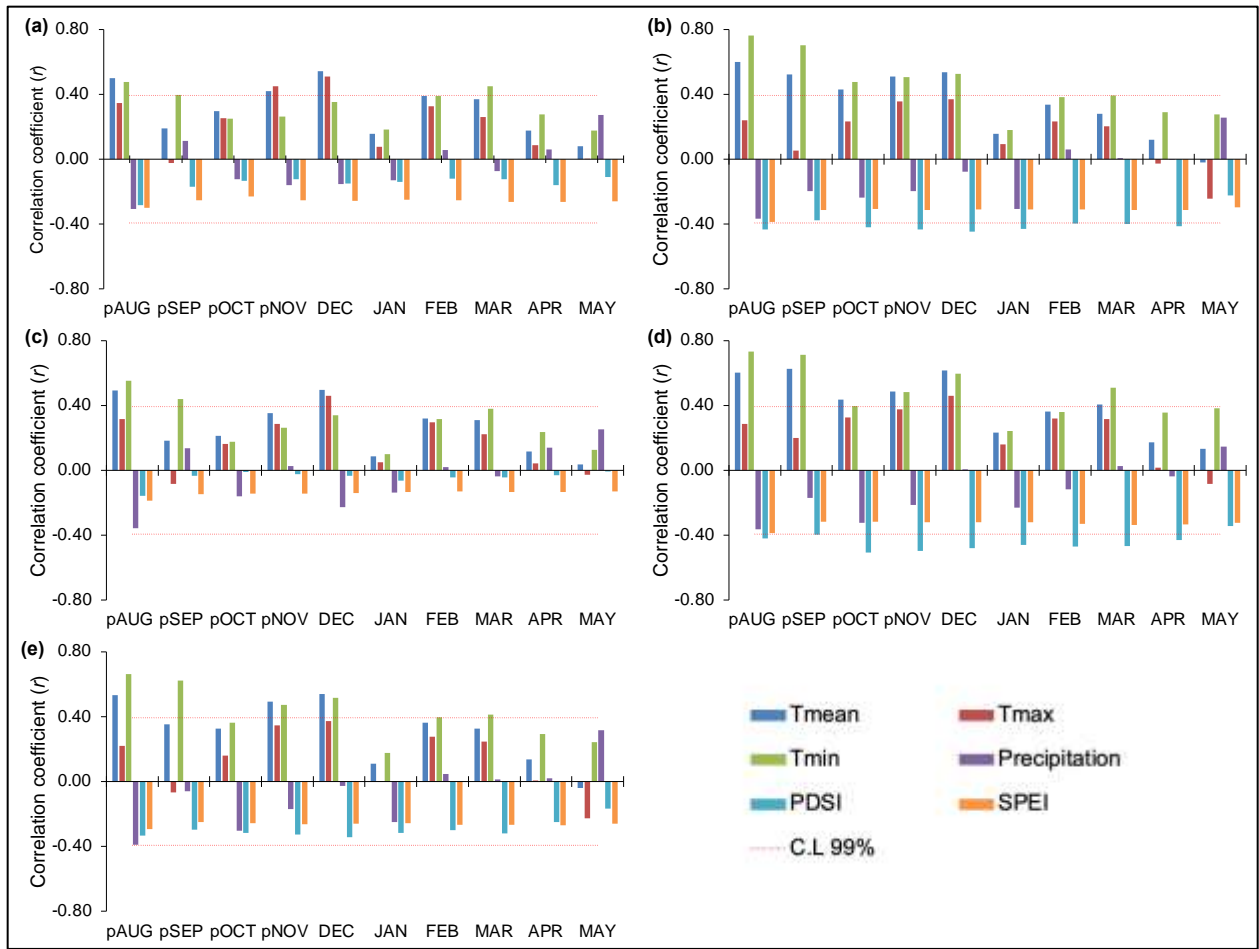


Figure 4: Composite diagram between yield and climate attributes namely winter temperature, mean annual temperature (MAT), PDSI (winter), winter precipitation (mm) for (a) Region A including the districts Banda, Lucknow Faizabad and Kanpur, and (b) Region B including district Jhansi



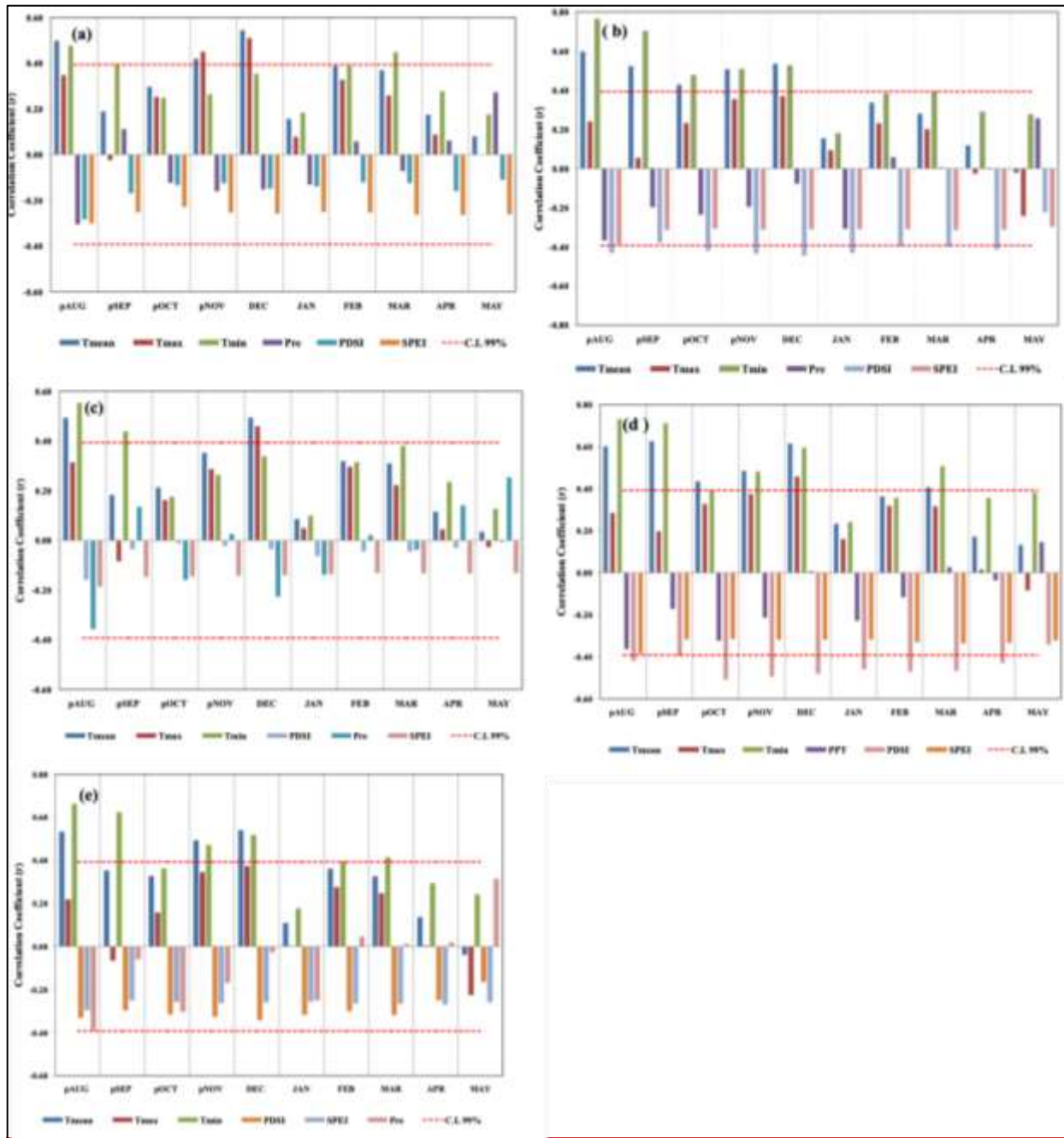


Figure 5: Correlation plot for wheat yield for (a) Banda, (b) Lucknow (c) Jhansi (d) Faizabad, and (e) Kanpur, with Mean temperature (Tmean), Maximum temperature (Tmax), Minimum temperature (Tmin), Precipitation (Pr), SPEI and PDSI. The dotted horizontal lines indicate the 95% and 99% CL.

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% C.L (Figure 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; Figure 6a). The RDA analysis also suggests that the previous year's average temperature of December is the most influencing factor for the production of yield in the study area. Further, the yield and climate relationship for the time period of 2000 to 2011 also suggest that the winter months have a strong correlation for all the five districts (Supplementary Figure 1), 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; Figure 6b). The trend in temperature and rainfall (CRU TS.4.03), PDSI [26] and SPEI ([Vicente-Serrano et al. 2010, 2013](#))[25,37] 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 Region A and B. The results showed the τ of MAT (τ_{Tmean}) was 0.484, 0.415 and the winter (τ) was 0.395, 0.360 whereas the MAP (Precipitation) -0.241, -0.149, Monsoon (Precipitation) -0.205, -0.122, Winter (Precipitation) -0.200, -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 Figure 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 period, particularly in Kanpur, and Banda region.

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

Axis	1	2	3	4	Total variance
1971-2011					
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					
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.

Table 4. Significant trend statistics (Mann Kendall trend and Sen’s Slope) for ~~Girded~~-gridded climate points which are Region A and Region B for all five districts of U.P based on Mann Kendall test.

Climatic Parameters	Kendall's tau	p-value	Sen's slope
Region A			
MAP (Pre)	-0.241	0.027	-7.618
Monsoon (Pre)	-0.205	0.061	-6.507
Winter (Pre)	-0.200	0.067	-0.604
MAT(Tav)	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(Pre)	-0.149	0.174	-3.631
Monsoon (Pre)	-0.122	0.266	-3.039
Winter (Pre)	-0.122	0.266	-3.039
MAT(Tav)	0.415	0.000	0.021
Winter (Tav)	0.360	0.001	0.028

Pre=Precipitation, Tav= Mean temperature, MAP=Mean annual precipitation, MAT=Mean annual temperature

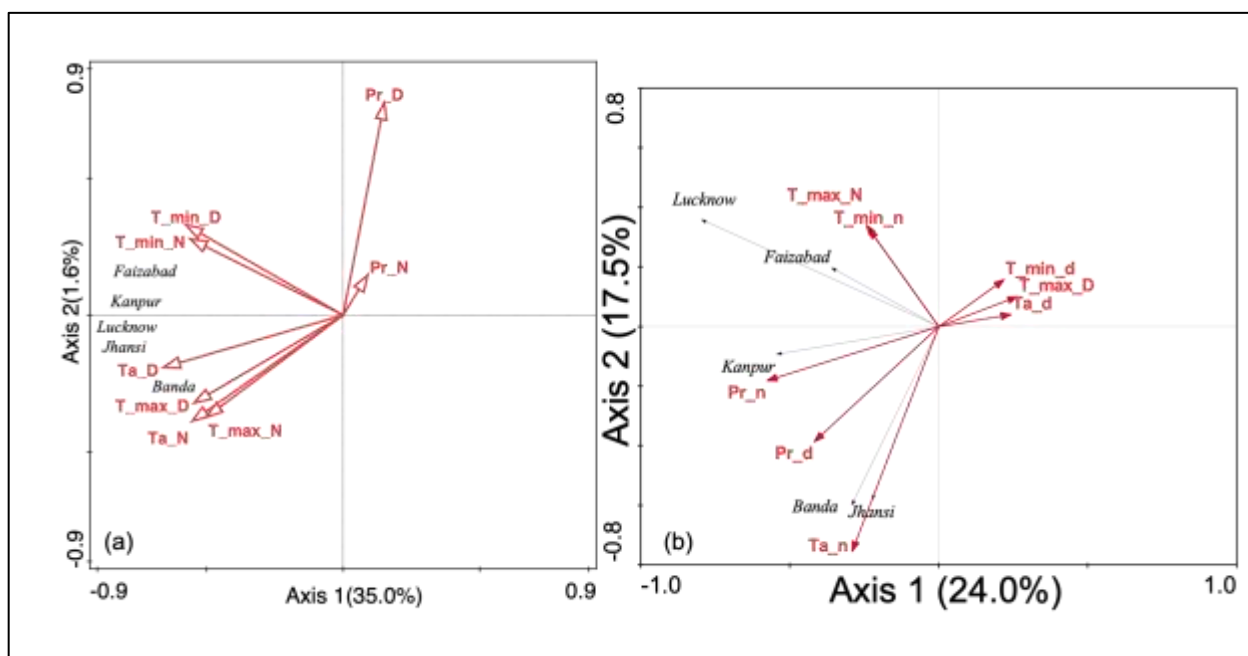


Figure 6: The RDA analysis showing the relationships between environmental factors and wheat yield. Time span covering the (a) 1971-2011 and (b) 2000-2011. [Climatic factors abbreviations: Ta_N, Ta_D, Tmax_N, Tmax_D, T_min_N, T_min_D are the previous year average temperature for November (Ta_N), December (Ta_D), Maximum temperature of November (Tmax_N), December (Tmax_D) and Minimum temperature of November (Tmin_N), and December (Tmin_D).

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 2013; Held 2013, Change 2014). For the 30-year average, the rate of warming scaled from the 1960s to around 2000 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 Figure 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 mainly due to use of different technologies and crop management practices. After 2000s, the increase in production can be attributed to the influence of winter temperatures (Supplementary Figure 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 climate forcing factors which influencing the yield. Crop yield variability is strongly related to regional temperature and precipitation anomalies (Iizumi et al. 2014)^[56]. 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 ($r = 0.95$; $n=115$, $p \leq 0.01$) 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.

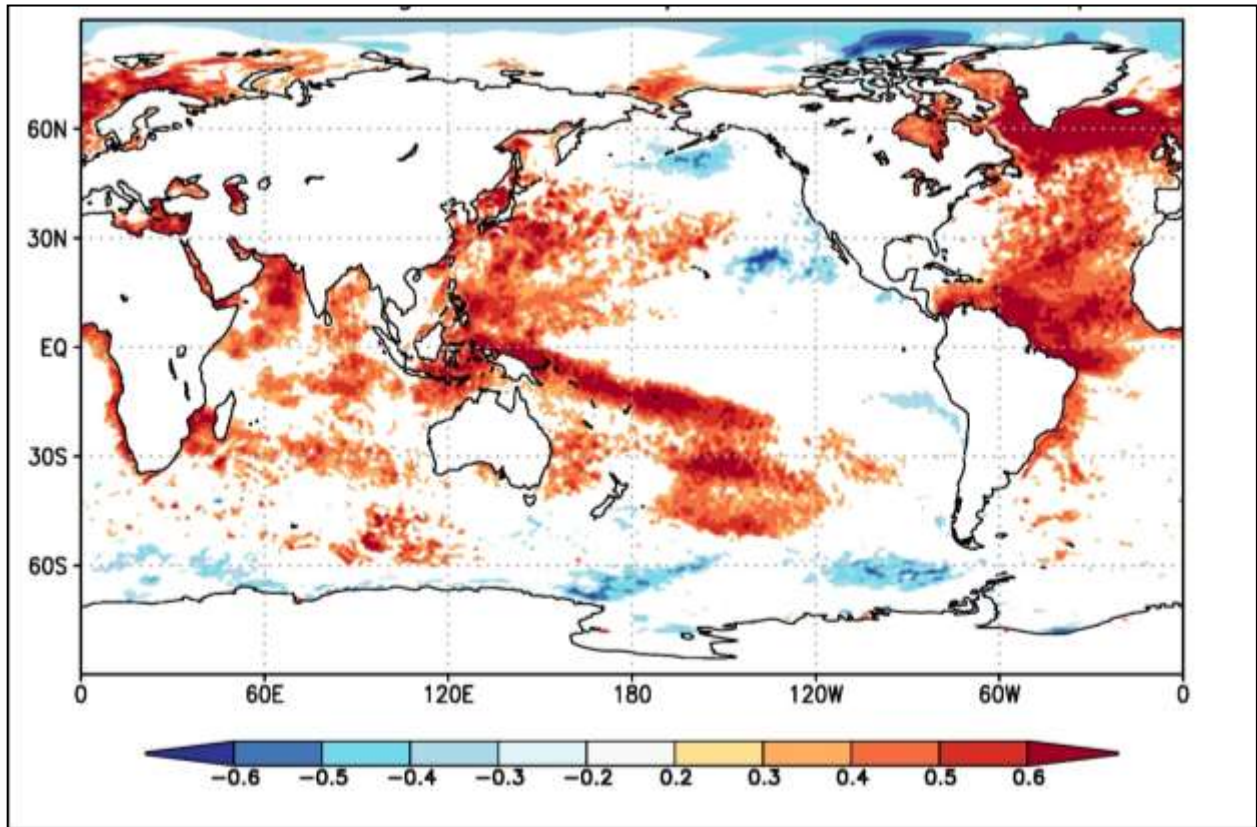


Figure 7: Spatial correlation between wheat yield and previous year November- December Sea surface temperature.

Moreover, the relationship shows the linkage and influence of mean temperature and SST on the annual yield of wheat (Figure 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 ~~centered~~centred in the Pacific Ocean in term of moisture availability evident by the significant positive correlation with SST of the Arabian

Sea and the Pacific Ocean (Figure 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 CO₂ between the atmosphere and the Earth's surface ([Stocker et al. 2013](#))[57]. The photosynthetic temperature acclimation processes are observed to increase carbon uptake and storage on land in the future ([Lombardozi et al. 2015](#))[58]. 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 (Figure 8a, b). When the increase in temperature and rainfall reaches its threshold value for the 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 1999](#))[29,59]. 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)[60,61]. The optimum temperature for maximum dry matter accumulation and the high night temperature is required for the growth of shoot (Acevedo et al. 2002)[62]. Besides, the foggy days during the early growth stages of the wheat crop ([Joshi et al. 2007](#))[23] and the seasonal variation in weather parameters could also influence pest and disease infestation to limit the yield ([Aggarwal 2008](#))[14]. 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](#))[63]. The positive and significant correlation with winter temperatures show that higher winter temperatures accelerate the 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) [64], and the grain filling period tends to be shorter, limiting time for grain growth ([Asseng et al. 2011](#))[65]. 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, and the excess is effectively lost to crops and does not contribute to yield. In reality,

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.

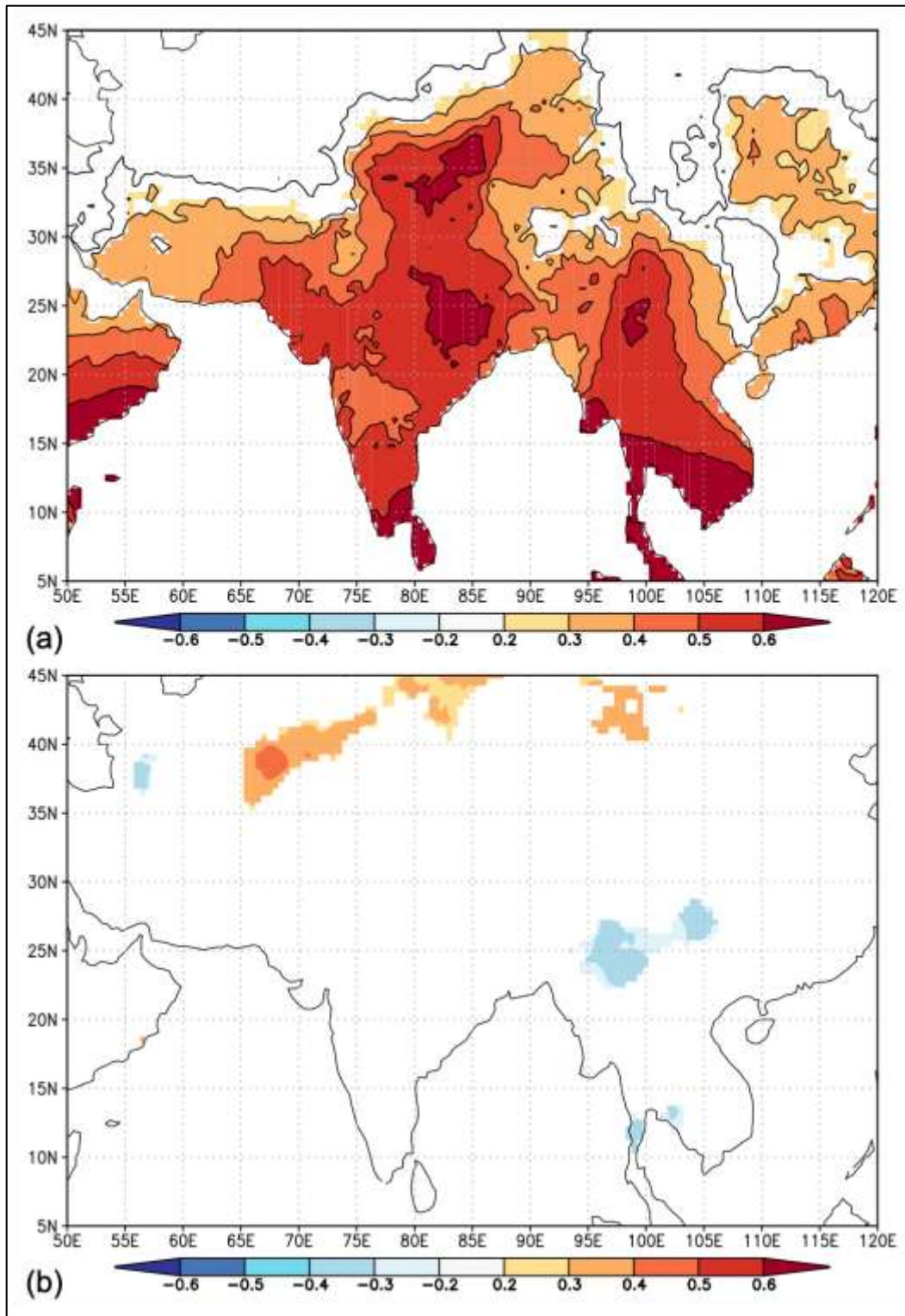


Figure 8: Spatial correlation between wheat yield and previous year November-December (a) temperature, and (b) precipitation and PDSI in and around adjoining area of U.P.

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 et al. 2000; Shekhar 2014; Shekhar and Bhattachryya 2015; Shekhar et al. 2022)[66–69].

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 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 address the effects of climate change before and after 2000, focusing on physiological responses and adaptation. Our findings confirm a statistically significant link between wheat yield and winter temperature variability in U.P 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 2010–2011C.E and lowest in the Banda district (4.02 Quintal/ha) during 1979–1980C.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. Moreover, the yield responded statistically significant linear relationship with temperature rise for the years 1971–2011C.E in all the study areas. We observed that pre-summer temperatures of UP ranges 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. As the temporal wheat production in UP and its linkage with winter warming is universal, regions or site-specific response; such responses need 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 in spite of all these advancements, winter temperature plays a significant role to limit the yield of this Rabi crop.

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Author Contributions

-All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Mayank Shekhar, Muskan Singh, Shaktiman Singh, Anshuman Bhardwaj, Rupesh Dhyani, Parminder S. Ranhotra, Lydia Sam, and Amalava Bhattacharyya. The first draft of the manuscript was written by Mayank Shekhar and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

About Data Availability

Data are however available from the corresponding authors upon reasonable request and with permission of coauthors.

Author Declarations

We declare that no funds, grants, or other support were received during the preparation of this manuscript.

Declaration of interests

We declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Agreement Statement

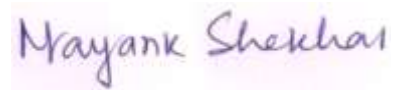
We the undersigned declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed.

We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We understand that the Corresponding Author is the sole contact for the Editorial process. He/she is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs

Signed by all authors as follows:

A handwritten signature in purple ink that reads "Mayank Shekhar". The signature is written in a cursive style and is placed on a light pink rectangular background.

Dr. Mayank Shekhar

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