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ORIGINAL ARTICLE

Impact of Climate Variability on the Rice Yield in Uttar Pradesh: an Agro-Climatic Zone Based Study

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Abstract

In the backdrop of the established fact that the climate and agricultural produce foster a close-knit relation, the present study explores the impacts of climate variability on the rice yields across diverse agro-climatic zones of Uttar Pradesh, India. The time-series non-parametric Mann-Kendall trend test was applied to study long term (both annual and seasonal) weather and yield data sets. Minimum temperature, encompassing all the zones, was found to be increasing within the range of 0.06 to 0.44 °C per decade. The '*kharif*' season maximum temperature trends were found increasing in most zones. In terms of annual and seasonal rainfall trends, the results were mostly non-significant, except for Bhabhar and Tarai Zone which had witnessed a very high decadal trend indicating towards the occurrences of intense rainfall events. North Eastern Plain Zone needs a special mention owing to its large number of extreme rainfall events in three categories (>50 to <100 mm/day; >100 to <150 mm/day; >150 mm/day). Considering the annual/seasonal temperature and rainfall variability in the region, the warming trend along with spatio-temporally uncertain rainfall is likely to inflict significant impact upon the rice crop. Consequently, there is a dire need to devise strategies capable of dealing with the impacts of the prevailing climate variability on rice yields in this state of India through development of suitable adaptation options for sustainable production. The continuous and rigorous studies into this field of agro-meteorology subjected to impact assessment call for international action plans that are designed in a frame of '*bottom-up approach*' or a '*local to regional to country level*' strategic implementation of adaptation options to sustain yields in the rice fields.

Keywords Adaptation · Agro-climatic zones · Climate variability · *Kharif* crop · Extreme events

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1 Introduction

At the door step of dual crisis of food and water scarcity, India being the second largest populous country of the world, stands face to face the daunting task of feeding the nation's population, which is projected to reach 1.7–1.8 billion by 2050 (Population 2016 World Bank 2016; Jain 2011). Rice is one of the major cereal crops in India, which accounts for more than 60% of total cropped area and 77% of total food production of the country (Singh et al. 2013; DES 2015). Since the 1950s, there has been substantial growth in total rice production along with both population (undertaking exponential rise) and irrigational water requirement, wherein the per capita surface water availability has drastically decreased since 2000 (Fig. 1).

Year-to-year rainfall variability and extreme weather conditions, such as droughts, floods and heat waves are regarded as the primary causes of annual fluctuations in yield. Nonetheless, subtler fluctuations in weather during critical phases of crop development can also have a substantial impact on yield. 80% of total annual rainfall received by the Indian subcontinent comes from the Indian Summer Monsoon Rainfall (ISMR). ISMR stays prevalent from June to September and till date 60% of agriculture in the country relies on it. To add to it, uncertainty in rainfall has affected irrigation water supplies leading to reduction in areas under irrigated crops, consequently bringing in more cultivation area under rain-fed crops. Gross Domestic Product (GDP) share of agriculture has shrunk from 57% in 1950 to about 14% in 2014, primarily due to the growth in other economic sectors. Nonetheless, this decline in the share of agriculture has not affected the importance of the sector in the Indian economy.

Rice crop experiences heat stress to varying degrees at different phenological stages due to its direct effect on grain number and grain mass. Strategic and applied research proved that climate variability and extreme weather events matter as much to crop production as do the mean values of climate variables in a given crop season (Rosenzweig and Parry 1994; Mall and Gupta 2000; Piao et al. 2010; Lobell et al. 2011;Chen et al. 2013; Sehgal et al. 2013; Pathak et al. 2014;Ray et al. 2015; Bhatta and Aggarwal 2015; Wang et al. 2015; Duncan et al. 2015;Mondal et al. 2015; Singh et al. 2018). India too is facing similar issues in crop yields due the weather adversities that have jeopardized the socio-economic demands. Therefore, to

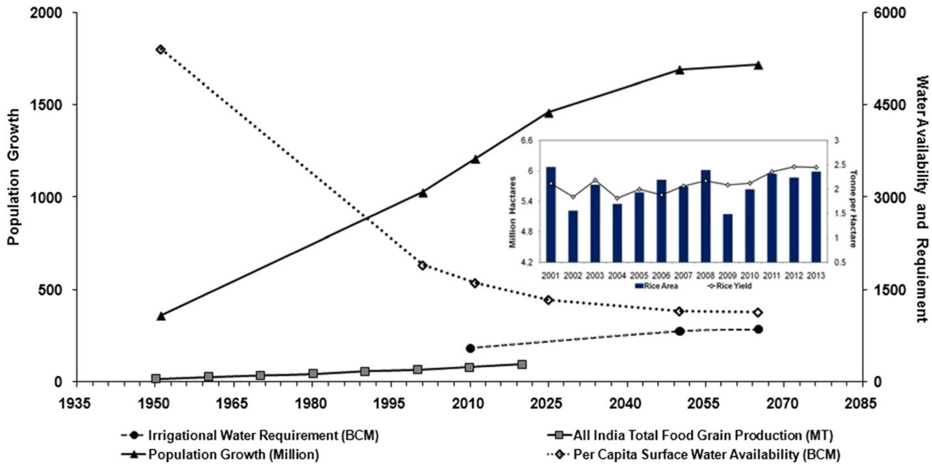

Fig. 1 Projections for India 2050 and 2065 population, total food-grain production, surface water availability and total irrigation requirement with recent rice area vs. rice yield for Uttar Pradesh in the incept [Source of Data: Jain 2011 and DES 2015]

sustainably suffice these demands, India has taken recourse to better policy and planning towards effective disaster risk reduction in the future (NATCOM 2012; Mittal and Ray 2015).

Increasing temperature trends of the order of 0.6 °C during the last 112 years over India have already been observed (IMD 2012). Recently, several studies reported a significant change in the pattern of temperature and no significant trend in rainfall and/or decreasing/increasing trends in rainfall and sharp decrease in rainy days (Singh and Sontakke 2002; Goswami et al. 2006; Dash et al. 2007; Guhathakurta and Rajeevan 2008; MoEF 2010; Guhathakurta et al. 2011; Subash et al. 2011; Kothawale et al. 2012; IPCC 2013; Das et al. 2014; Dubey and Kumar 2014; Oza and Kishtawal 2015). On an average, rainfall intensities have been found increasing country wide but the number of rainy days is decreasing and the trend is expected to continue till the end of the twenty-first century (Goswami et al. 2006; Pai et al. 2015). A number of studies have been carried out to understand the crop-weather relationship in the Indian perspective (Aggarwal and Mall 2002; Mall and Gupta 2002; Selvaraju 2003; Mall et al. 2006; Singh et al. 2010; Kumar et al. 2011; Swaminathan and Kesavan 2012; Prasanna 2014; Mondal et al. 2015; Singh et al. 2016; Mall et al. 2018) as well as the dependence of the Indian economy on its agriculture (Preethi and Ravedkar 2012; Ravedkar and Preethi 2012). India's policy-making has already taken serious note of climate variability and change that has been affecting the nation's agricultural produce. The introduction of National Action Plan for Climate Change (NAPCC), adopted in 30th June 2008, National Adaptation Fund (NAF) and an overall shift towards sustainable practices to achieve the nation's developmental goals stand firm to prove that the Indian government is active to ensure an effective implementation of these policies. The National Mission for Sustainable Agriculture (NMSA) and National Mission on Strategic Knowledge on Climate Change (NMSKCC) are the two of the eight missions under the NAPCC which were designed to mitigate the climate induced risks and to encourage research, innovation and the expansion of the Climate Smart Agriculture (CSA) like practices (NAPCC 2008).

Climate projections developed for India for the 2050s indicate a 2-4 °C increase in average temperature and decrease in the number of rainy days (Kumar et al. 2006; MoEF 2010). It is projected that by 2100, the *kharif* season (June to October-monsoon season in India) temperature would warm by a minimum of 0.7 °C - 3.3 °C, whereas rainfall would be −7% to 37% wetter (Birthal et al. 2015). Also there are studies that say that if measures to uphold the rice yields in India are not enacted immediately, by 2050, India would be more of an importer of rice than an exporter (Teng et al. 2016; van Oort and Zwart 2017).

Uttar Pradesh is the most populated (199.6 million; 17% of India) state and has distinguished itself as the 'agricultural hub' on account of its largest share of rice area (13%, IIIrd in India, 5.95 Mha) and production (13%, IIIrd in India, 14.0 MT). The state also faces tremendous stress on its water resources due to the huge agriculture industry (Mall et al. 2006). As long as the rainfall variability and change remains a threat for the water availability, it would keep flinging in difficulties to cultivate the water-intense crops. The rising concerns like the high climate variability, decreasing per capita water availability and the rising food demands of the growing national population are yet to be explored for their inter-dependencies to combat the crisis. This crisis is a daunting challenge for the stakeholders and the decision-makers, and to handle, they must look for effective adaptive measures capable of ensuring sufficient water and food supplies for all.

In the light of the above discussion, it is very important to make the rice crop production more resilient to climate variability and change. It is noteworthy that there are plenty of studies in India on climate and extreme weather events, but they are only few for Uttar Pradesh and none expanding over the states' agro-climatic zones. Therefore, the present study aimed to examine the long-term annual and seasonal climate variability and extreme events across various agro-climatic zones of Uttar Pradesh, and its impact on rice growth and yields. Also, an attempt has been made to analyze the impact of extreme weather upon phenological phase(s) of rice crop with a special reference to better agronomic management of weather constraints to ensure sustainable production in the region.

2 Materials and Methods

2.1 Study Site

Uttar Pradesh is located within the Indo-Gangetic Plains (IGP) of India, spreading between 23°50'–30°45' N latitude and 77°04'–84°38' E longitude, as shown in Fig. 2a. It is divided into nine agro-climatic zones on the basis of rainfall, temperature and soil. Table 1 enlists a detailed description for all these zones (including their abbreviations that are used in the discussion further below).

2.2 Data and Analysis

The observed daily long-term maximum temperature and minimum temperature data from 1971 to 2013 and rainfall data from 1971 to 2013 were obtained from the Indian Meteorological Department (IMD), New Delhi. Rice yield data were obtained from the KrishiBhawan, Uttar Pradesh and Ministry of Agriculture, New Delhi (DES 2015). Mann Kendall Test at 0.05% significance level was applied to detect the trend in both temperature and rainfall data. For *rice or kharif* season, temperature extremes were considered whenever the temperature rose beyond 35 °C and/or fell below 20 °C, which might have affected the crop growth and development, and thus the final yield. Apart from that, rainfall at the annual/seasonal (monsoon, pre-monsoon, post-monsoon and winter) time scales with analysis of rainy days and extreme rainfall variations was also studied. Mann-Kendall test is a statistical test, which is widely used for the long-term climatological and hydrological time series data. Rainy days are categorized with threshold of ≥2.5 mm per day as given by criteria of IMD. Whereas, extreme rainfall was categorized under three categories of thresholds, i.e., >50 mm to <100 mm /day, >100 mm to <150 mm /day and > 150 mm/day. Apart from that, rainfall in each of the crop growth stages were compared with that of the annual rice yields to minutely examine whether growth stage rainfall held any crucial role in the rise or fall of the yields. This is followed by assessment of phase-wise impact of temperature and rainfall over the crop yields, so as to identify the most affected phase(s) which plausibly lead to final yield variability.

3 Results and Discussion

3.1 Variability and Trends in Annual and Seasonal Temperature

Although India's overall average annual surface temperature has increased significantly over the past century (IMD 2012), there are remarkable zonal contrasts as far as increase in temperature is concerned (Fig. 2b). The largest warming was found in WPZ with an annual

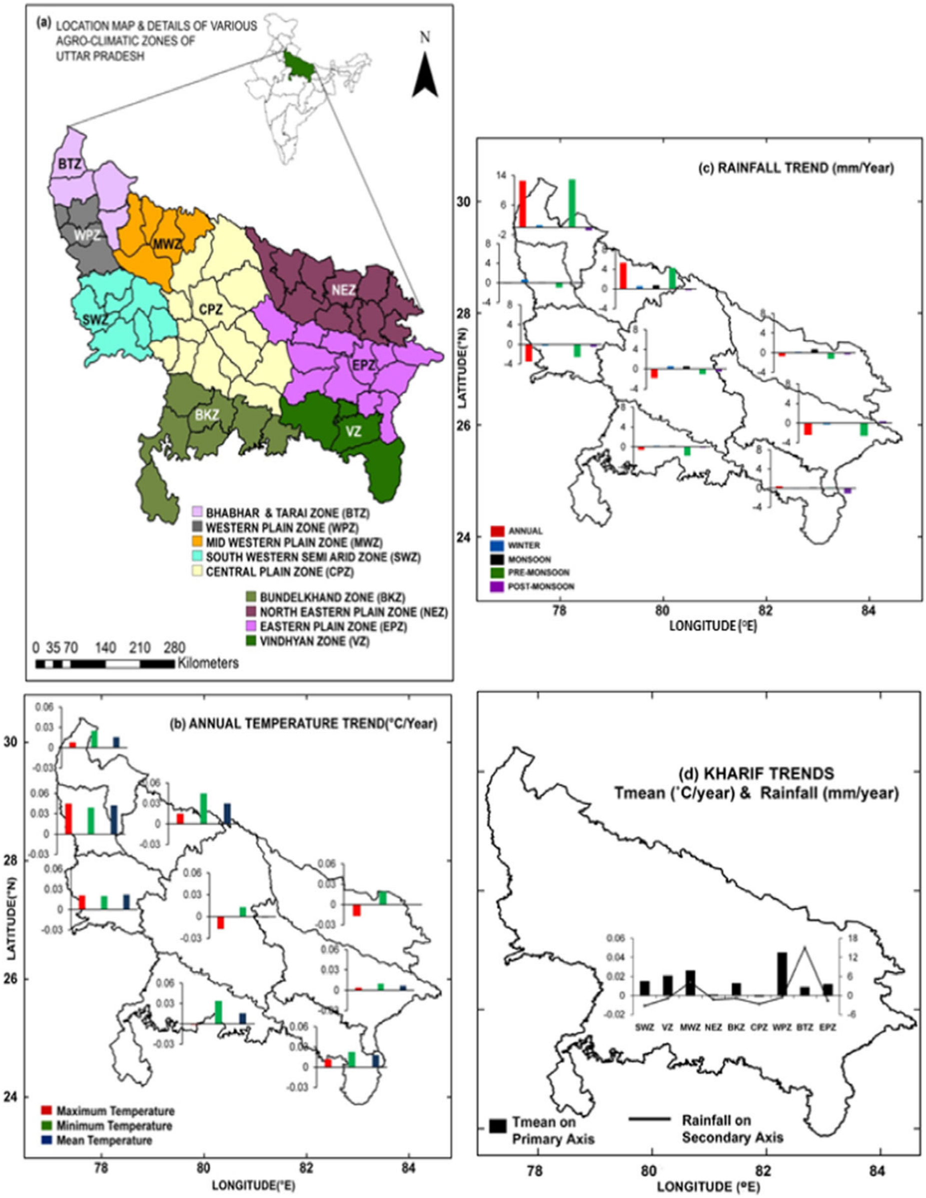

Fig. 2 **a** Study area: Nine Agro-climatic Zones of Uttar Pradesh; **b** Annual Temperature Trend in Agro-climatic zones of Uttar Pradesh; **c** Annual Rainfall Trend in Agro-climatic zones of Uttar Pradesh; and (d) *Kharif* Temperature and Rainfall trends

trend of 0.4 °C per decade and marked 2002 being the warmest year with positive anomaly of 1.9 °C. Whereas, MWZ was found to have a trend of 0.3 °C per decade and 2006 being the warmest year marked by a positive anomaly of 1.6 °C. On the contrary, CPZ was characterized by a cooling trend, i.e., 0.1 °C per decade wherein, no discernible trend was found in NEZ in terms of annual temperature variability. As for the diurnal temperature range, it is distinctly increasing in the cases of NEZ and CPZ, as in these two zones the maximum temperature

Table 1 General description of the diverse nine Agro-Climatic Zones of Uttar Pradesh

Agro-climatic zones	Averages of *Kharif* season temperature and rainfall	Climate and soil type	Gross irrigated area (10^3ha)	Total geographical area (ha)	Rice area (%)	Moderate drought years	Severe drought years
South-western Semi-Arid Zone (SWZ)	29.6 °C, 618 mm	Semi-arid Sandy Loam, Sandy soil, Alluvial	2244.96	2,234,222	9.8	1974, 1979, 1981, 1987, 1999, 2000, 2001, 2002*, 2004*, 2012*	2009
Vindhyan Zone(VZ)	29.9 °C, 820 mm	Sub-humid Red laterite & Black Soil	678.57	1,381,844	16.1	1972, 1975, 1991, 1992, 2005, 2009*	–
Mid-Western Plain Zone (MWZ)	28.5 °C, 933.5 mm	Sub-humid Clay & Sandy Loam, Alluvial	2218	1,697,125	28.3	1971, 1973, 1975, 1976, 1978, 1986, 1991, 2008	–
North Eastern Plain Zone (NEZ)	29 °C, 1174 mm	Humid-sub Tropical Sandy Loam,Silty loam	2097	2,955,485	43.6	1972, 1976, 1979, 1986, 1990, 1992, 2002*, 2011	–
Bundelkhand Zone (BKZ)	28.9 °C, 797.4 mm	Dry sub-humid to arid Mixed red & black Soil	531.5	2,961,006	2.5	1979, 1986, 1994, 2002*, 2004*, 2009*	–
Central Plain Zone (CPZ)	29 °C, 819 mm	Dry sub-humid to Semi-arid Clay & Sandy Loam, Silty Clay	4445.3	5,647,307	24.6	1974, 1976, 1979, 1987, 1992, 1993, 2002*	–
Western Plain Zone (WPZ)	28.1 °C, 674 mm	Semi-arid Sandy Loam, loam, Silty loam	1213	1,637,424	9.7	1979, 1982, 1989, 2001, 2004*, 2006*, 2007, 2008, 2012*	1987
Bhabar and Terai Zone (BTZ)	25.5 °C, 1201 mm	Humid Clay & Sandy Loam, Silty loam to loam	1440.3	1,847,319	27.6	1979, 1980, 1983, 1986, 1990, 2002*, 2003, 2010	1978
Eastern Plain Zone (EPZ)	29.5 °C, 841 mm	Dry sub-humid Sandy Loam, Sodic, Clay loam, Alluvial	3546.2	3,808,718	40.6	1972, 1977, 1979, 1994, 1998, 2009*, 2010	–

*Recent El Nino Years Note: Fifth coloumn contains authentic information from Integrated Watershed Management Programme (I.W.M.P) in Uttar Pradesh Perspective and Strategic Plan (2009–2027), Government of Uttar Pardesh, India (2009) (http://dolr.gov.in/sites/default/files/SPSP_Uttar%20Pradesh.pdf) showed an increasing trend, whereas the minimum temperature showed a decreasing trend. Across the state, on an average, the minimum temperature undertook a rising trend within the range of 0.1 to 0.4 °C. In general, the maximum temperature was also observed to be increasing in all zones except in NEZ and CPZ. Rice or *kharif* season also showed similar trend to that observed for annual temperature (Fig. 2d). The Mann-Kendall test was applied to detect trend(s) in the long term temperature data (Table 2). Across the state the variation in annual mean temperature ranged between 20.6–26.1 °C. The Mann-Kendall Statistic (S) value for maximum temperature indicated a positive upward trend in all the zones except in NEZ, CPZ and EPZ. In the entire Uttar Pradesh state, the largest minimum temperature increase (i.e., 3.7 °C) was estimated in BKZ in year 2006 and the largest maximum temperature increase (i.e., 2.6 °C) was estimated in WPZ in year 2002.

3.2 Variability and Trends in Annual and Seasonal Rainfall

The annual as well as seasonal trends over the different agro-climatic zones varied greatly from each other with remarkable zonal contrasts. On an average the annual and rice/*kharif* season rainfall trends were found to be increasing at 1.1 and at 0.7 mm/year, respectively, over the state. Nevertheless, this trend seems to be biased by the exceptionally high annual rainfall trend of 13 mm/year that characterized BTZ, and on exclusion of BTZ's rainfall, the trend for the whole state was a distinct overall decreasing trend at −0.8 mm/year. The trends for winter, post-monsoon and pre-monsoon seasons were estimated at 0.22, −0.38 and 0.24 mm/year, respectively. SWZ (−0.5 mm/year), EPZ (−0.3 mm/year) and CPZ (−0.2 mm/year) showed considerable declining trends, whereas MWZ and BTZ showed remarkable rising trends (0.51 and 0.91 mm/year, respectively; Fig. 2c). The obtained statistical estimates from running the Mann-Kendall (MK) test on rainfall datasets for the various zones are compiled in Table 2. The comparative assessment of p-estimate with that of the significance level α (alpha) = 0.05 is the criteria in this statistical test as far as acceptance or rejection of the null hypothesis. When the p value is less than α, H_0 is rejected, indicating the existence of a statistically significant trend in the data, whereas if the p value is found more than α, H_0 is accepted denying existence of any trend whatsoever. The MK test statistic (S) for various zones of the state cannot be put in any trend as there exist large fluctuations; the estimates have been calculated as high as 400 for BTZ and as low as −105 for SWZ. In between are VZ, CPZ and NEZ, whereas BKZ and MWZ exhibit poor S.

3.3 Vulnerability of Rice Yield to Climate Variability and Extreme Events

An exhaustive study undertaken by Ray et al. (2015) underscores the fact that considering all the global spread of rice producing regions, about 53% of the region has experienced impact of climate variability on the yield. In the case of India, they suggested that during the span of study, i.e., 1979–2008, almost 15% to 30% of rice yield variability was due to climate. In the case of Uttar Pradesh, extreme temperature and rainfall events affected the yields, as well as normal rainfall due to its late arrival in the form of monsoons. Not only India but also other rice producing countries like China, Vietnam, Thailand, Philippines, Bangladesh, Indonesia have also experienced fluctuations in the yields of their rice crops grown in various crop-seasons. Indonesian rice yield has a very close knit relation with arrival of monsoon rains and recent delays in the monsoon has affected the rice yields of the South-Asian rice producing countries (Naylor et al. 2007). An all China-wide research lead by Chao et al. (2014) undertook the impact assessment of rice yield variability in response to changing climate over a dataset of

Table 2 Statistical analysis of *Kharif* season Rainfall and Annual Mean, Maximum & Minimum Temperature over various Agro-Climatic Zones of Uttar Pradesh

Stations		*Kharif* Season						Annual					
		Mean	CV (%)	Kendall's tau	S	p	Sen's Slope	Mean	CV (%)	Kendall's tau	S	p	Sen's Slope
SWZ	Tmax	34.9	3.1	0.13	121	0.21	0.01	31.8	2.9	0.23	211	0.03	0.02
	Tmin	24.4	2.7	0.15	137	0.16	0.02	18.5	3.3	0.23	207	0.03	0.02
	Tmean	29.6	2.2	0.19	169	0.08	0.01	25.1	2.5	0.25	225	0.02	0.02
	Rainfall	618	29.7	−0.07	−61	0.50	−1.12	713	28.9	−0.12	−105	0.26	−1.12
VZ	Tmax	34.6	2.6	0.21	195	0.04	0.02	32.6	1.9	0.18	161	0.09	0.02
	Tmin	25.1	3.4	0.23	211	0.03	0.03	19.5	3.9	0.25	223	0.02	0.03
	Tmean	29.9	2.3	0.24	221	0.02	0.02	26.1	2.1	0.24	215	0.02	0.02
	Rainfall	820	26.6	0.22	182	0.04	6.45	936	25.1	0.15	43	0.15	5.37
MWZ	Tmax	33.3	3.7	0.13	119	0.22	0.01	30.4	3.1	0.14	125	0.19	0.02
	Tmin	23.8	4.2	0.32	289	0.00	0.03	18.1	6.1	0.37	337	0.00	0.04
	Tmean	28.5	3.7	0.19	173	0.07	0.02	24.2	3.9	0.23	209	0.03	0.03
	Rainfall	933.5	28.2	0.09	74	0.41	3.42	1045	26.4	0.04	141	0.71	1.05
NEZ	Tmax	33.4	2.2	−0.22	−199	0.04	−0.02	31.2	2.3	−0.28	−249	0.01	−0.02
	Tmin	24.6	2.4	0.23	209	0.03	0.01	18.1	2.7	0.35	319	0.00	0.02
	Tmean	29.0	1.5	−0.09	−83	0.39	−0.00	24.6	1.7	−0.04	−35	0.72	−0.00
	Rainfall	1174	29.3	0.03	28	0.76	0.99	1287	28.2	0.09	83	0.38	3.35
BKZ	Tmax	34.3	3.7	−0.02	−25	0.80	−0.00	32.2	2.4	0.01	11	0.92	0.00
	Tmin	23.5	4.8	0.37	333	0.00	0.04	18.1	7.7	0.19	173	0.07	0.03
	Tmean	28.9	2.9	0.16	143	0.14	0.01	25.1	3.2	0.21	189	0.05	0.02
	Rainfall	797.4	29	−0.02	−14	0.88	−0.97	861	25.9	0.03	25	0.79	0.97
CPZ	Tmax	33.8	2.3	−0.14	−119	0.20	−0.01	31.4	1.8	−0.30	−259	0.01	−0.02
	Tmin	24.2	1.3	0.20	173	0.06	0.01	18.2	2.1	0.34	293	0.00	0.02
	Tmean	29.0	1.4	−0.03	−27	0.78	−0.00	24.8	1.5	−0.04	−37	0.69	−0.00
	Rainfall	819	31.5	0.00	0.0	0.99	0.02	900	28.4	0.25	45	0.07	0.69
WPZ	Tmax	33.3	3.3	0.32	281	0.00	0.04	29.9	3.4	0.34	293	0.00	0.04
	Tmin	22.9	4.2	0.40	348	0.00	0.04	18.2	4.4	0.47	406	0.00	0.04
	Tmean	28.1	3.3	0.39	343	0.00	0.04	24.0	3.5	0.43	371	0.00	0.04
	Rainfall	674	32.0	0.01	4	0.97	0.12	781	35.7	−0.11	−97	0.30	−4.12
BTZ	Tmax	30.5	1.9	−0.01	−7	0.95	−0.00	27.0	1.9	0.10	91	0.35	0.01
	Tmin	20.5	1.9	0.45	411	0.00	0.02	14.3	3.2	0.48	431	0.00	0.02

Table 2 (continued)

Stations		*Kharif* Season						Annual					
		Mean	CV (%)	Kendall's tau	S	p	Sen's Slope	Mean	CV (%)	Kendall's tau	S	p	Sen's Slope
	Tmean	25.5	1.5	0.21	193	0.04	0.01	20.6	2.0	0.37	333	0.00	0.02
	Rainfall	1201	33.5	0.28	185	0.02	13.9	1415	27.5	0.46	176	0.03	10.92
EPZ	Tmax	33.9	2.7	0.06	53	0.59	0.00	31.7	2.0	−0.01	−11	0.92	−0.0
	Tmin	25.1	2.7	0.13	119	0.22	0.01	19.5	2.9	0.13	115	0.23	0.01
	Tmean	29.5	1.7	0.14	125	0.19	0.01	25.6	1.4	0.11	97	0.32	0.01
	Rainfall	841	22.4	−0.14	−114	0.20	−3.07	910	21.8	−0.11	−95.0	0.31	−2.67

50 years. They found that the decrease in diurnal temperature conditions have affected the single-rice cropping system and the production has fallen down by 3% from its long term average production from 1961 to 2010. Wherein, reduction further increases by 6.2% when combined with changes in precipitation. For double cropping system, only the decrease in diurnal temperature was found to be significant with production reduced by 2.0% from the long term average. A recent study carried out in Vietnam indicated that though average seasonal rainfall positively affected the rice yields, the average seasonal maximum temperature adversely affected the yield in both rice growing seasons (Chung et al. 2015). The three major ecotypes of rice grown in Bangladesh were studied with respect to the observed dataset available for the period of 1981–2010 (Ara et al. 2017). Spatio-temporal variations in yields of these three ecotypes were found to be more susceptible to temperature than to rainfall. As for Philippines, a 2018 study highlights the El-Nino and Southern Oscillation phenomena, which modulated to a great extent the available soil moisture, thus affecting the rain-fed rice yields with only a limited impact on yield due to temperature variability playing the major role (Stuecker et al. 2018). With all the above discussions, it is obvious that temperature or rainfall variability affect rice yields, depending on geographical location along with soil properties or the popular crop variety grown or agricultural systems and their regimes. The above discussion underscores the fact that the specific variability caused by climate parameter(s) could be an appropriate approach to understand the actual reason(s) behind the impact of climate upon yield. As for India, the rice-growing season almost coincides with the arrival of the southwest monsoon, which brings rainfall ranging from at least 713 mm to 1415 mm across the different agro-climatic zones of the state (Table 1). Over the past five decades, rice yields have increased significantly despite of both the considerable annual rainfall variability and the remarkable regional contrasts in the maximum and minimum temperature trends, but the annual yield variability showed the impact of climate variation. During *kharif* season, the critical mean temperature for flowering and fertilization ranges from 16 to 20 °C. High temperature, especially during the night, leads to loss of reserved food through greater respiration (Peng et al. 2004). For higher grain yield, a day temperature of 25 to 32 °C and night temperature of 15 to 20 °C is preferable. Temperature beyond 35 °C affects both the pollen shedding as well as the grain filling. It is well known that mild temperature of night and clear sunny weather during daytime is better for high yield of rice, but temperature less than 15 °C is neither conducive for the panicle initiation nor for the crop growth (Rao et al. 2014).

Over Uttar Pradesh the *kharif* season was marked by an increase in minimum temperature ranging between 0.06 to 0.44 °C per decade across the state, inclusive of all zones. Such a rising trend in temperature may bear negative impacts on *kharif* rice crop. And the rice yields declined due to the rise in minimum temperature, e.g., in the cases of MWZ, BKZ, WPZ and EPZ in recent years (after 2000) the yield was affected due to the same reason (Fig. 4a). In SWZ, years 2002, 2007 and 2009 witnessed maximum number of days with temperature >38 °C for more than one to three weeks consecutively during the vegetative phase, which caused drastic decline in the rice yield. During the same year, continuously for two to three weeks, occurrences of maximum temperature with a count of >35 °C were also observed in the reproductive and ripening phases of the crop leading to yield reduction.

In BTZ situated at the north-west corner of the state, during the El Nino years like 1976, 1982 and 1987, the reported rice yields were found lower than the crop's long period yield averages (Fig. 4a). The middle most situated zones of the state, i.e.,CPZ, in 1972, 1976, 1982 and 1987 El Nino years witnessed an overall reduction in rice yields. In EPZ, during the El Nino years 1972, 1976, 1982 and 1987 the overall yields were also lower than the long period average of rice crop of the zone but not severely lower. The above findings regarding BTZ, CPZ and EPZ agree with the findings of AshaLatha et al. (2012) who found that in a district level study of Southern India ~92% of its sampled farmers confirmed that the reduction in the rain-fed crop yield was due to reduction in rainfall. Nonetheless, in another study, increase in grain yield with increase in rainfall was reported (Bhattacharya and Panda 2013). The study confirmed that for each mm increase in rainfall resulted in an average of 0.35 kg/ha increase in rice grain yield. Koshal (2014) concluded that the rice crop in IGP depends on ISMR. A keen observation of the yield variability across almost all the zones for the given study period brought to light the fact that after 1990s, despite the occurrences of El Nino or La Nina events or of regional droughts, the crop yield did not undergo any significant decline.

At BKZ, annual rice yields, considering for example years 2007 and 2008, showed large gaps. In 2007, the rice yield went down by 20%, whereas in 2008, just the next year, the yield went up by 98% when compared with the mean yield of the zone. 2008 was marked by higher minimum temperature than that of 2007. Apart from this, during 2008, the maximum temperature had also dipped very low (~ 4 °C below the mean of 34.3 °C), accompanied by a significant rainfall in the crop season (Fig. 3a, b). A keen look into the extremes pinpoints that neither 2007 nor 2008 was demarcated as any kind of a drought year, and 2007 even did not have any worth mentioning records of rainy days or not even any rainfall extremes that might have acted as potential reason in pulling down the yield (Fig. 3b). A number of studies pertaining to crop variability and changing climate have found that the rise in temperature (average/maximum/minimum) in tandem with CO_2 fertilization (both only to a certain extent) along with the crop variety and management practices help increasing the rice grain yields (Devkota et al. 2013; Rani et al. 2011). However, in our case, the

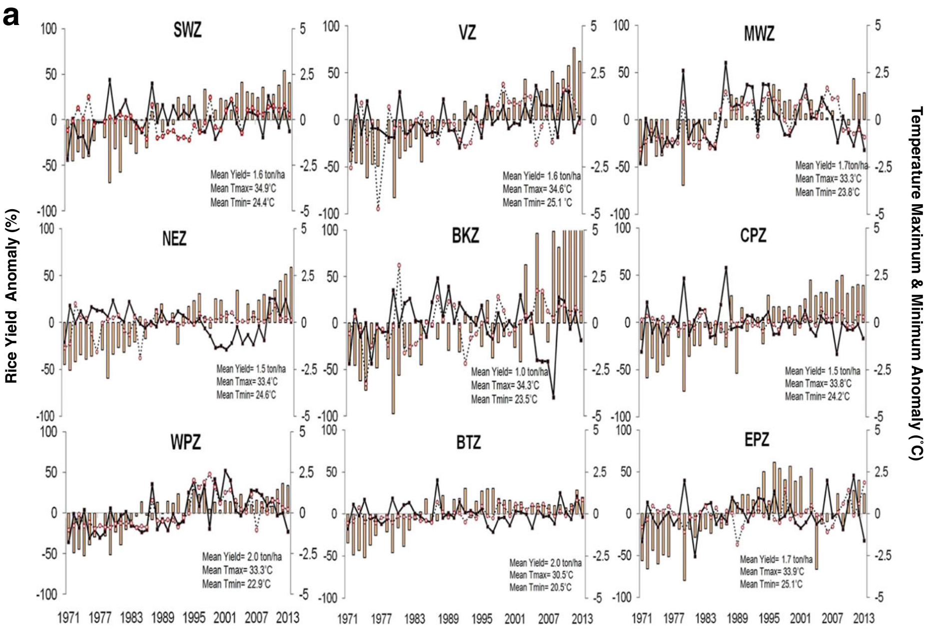

Fig 3 **a** Sensitivity of Rice Yield to Maximum & Minimum Temperature over different Agro-Climatic Zones (Bars represent Rice yield anomaly; Black line represents Tmax anomaly whereas Dotted line represents Tmin anomaly; **b** sensitivity of Rice Yield (on primary axis, grey bars) to *Kharif* Rainfall (on secondary axis, solid lines) across different Agro-climatic Zones of Uttar Pradesh

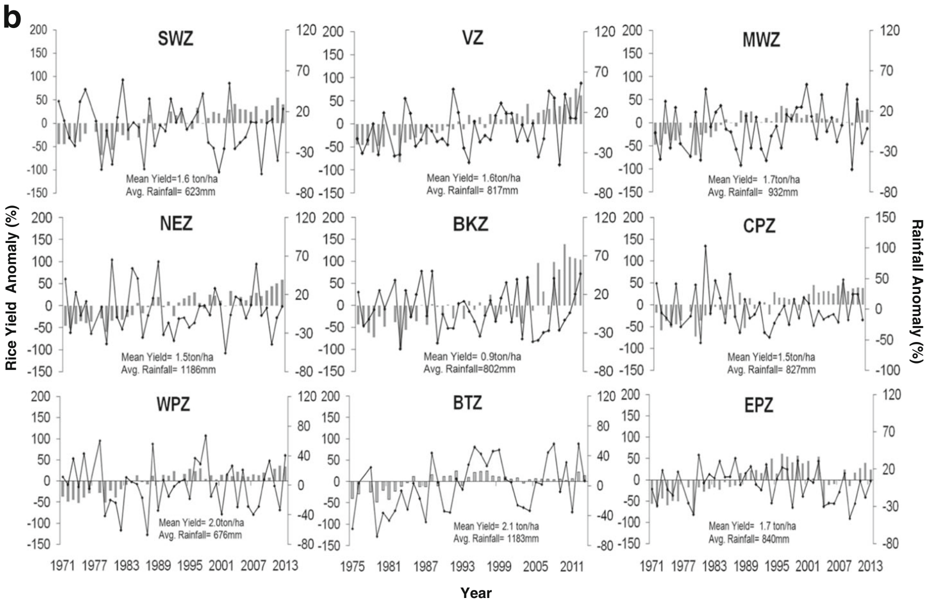

Fig 3 (continued)

yield difference in these consecutive years could not be explained in this line of thought. The increased temperatures (either maximum or minimum or both together) have rather played a detrimental role as far as the rice yields are concerned in the region. Liu et al. (2017) conducted a similar study in China to understand how the increased CO_2 levels in combination with the high temperatures affected the rice yields. They identified the effect to be adverse for crop yield. From 2008 onwards, it can be noted that even when the minimum temperature have risen, the yields have been sustained to the same level (Fig. 3a). The same level of yield indicates towards the management applications undertaken by the farmers to protect rice yields from the temperature variability which had affected yields consistently in the past, e.g., in 1995, 1997, 1998, 1999, 2001 and 2002.

As far as MWZ is concerned, the rice yields of 2010 and 2011 had great contrast, with the difference between the two years being nearly 49% (Fig. 3a, b). The seasonal rainfall study showed that year 2010 suffered >40% of rainfall deficiency, whereas year 2011 received ~35% more rainfall than the long term average seasonal rainfall of this zone. As for the temperature extremes, the number of days recorded to have crossed >35 °C in terms of maximum temperature ranged from 18 to 20 for both years (Fig. 4a). The critical mean temperature for flowering and fertilization in rice ranges from 16 to 20 °C. Therefore, high temperature, especially during the night, leads to loss of the reserved food through greater respiration. For higher grain yield, day temperature of 25 to 32 °C and night temperature of 15 to 20 °C is preferable. Temperature beyond 35 °C affects not only pollen shedding but also grain filling (Hatfield and Prueger 2015; Krishnan et al. 2011). It is well known that mild temperature of night and clear sunny weather during day time is better for high yield of rice, but temperature less than 15 °C is neither conducive for panicle initiation nor is it for crop growth (Peng et al. 2004). The number of days recorded for <20 °C in terms of minimum temperature were less in 2010 when compared with 2011, which indicates that 2010 was warmer than 2011. In 2010, there were 4 rainfall extremes in the range >50 mm and <100 mm and a single event of >100 mm and <150 mm. In contrast 2011 had to face only 2 events of >50 mm and <100 mm

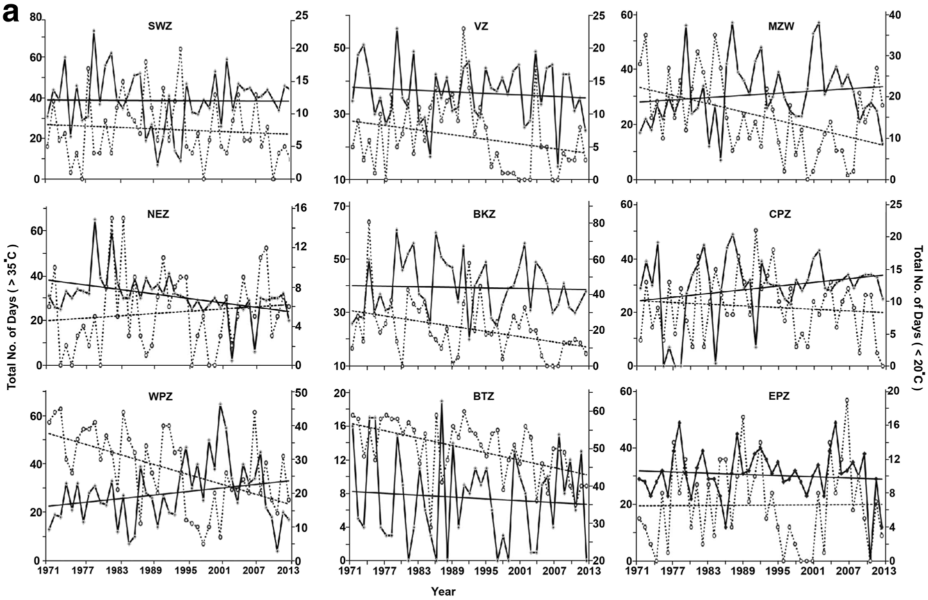

Fig 4 **a** Number of days estimated for temperatures >35˚C and <20˚C in Rice growing season (Dark line represents total no. of days for temperature >35˚C and dark straight line is the trend line, whereas the dotted line represents the total no. of days for temperature <20˚C and dotted straight line is the trend line); **b** Comparative study of annual rainfall anomaly and rainy days with % contribution of rainfall extremes of different category for each of the agro-climatic zones of Uttar Pradesh (In the Pie chart: Blue represents % of total days with >50 mm and <100 mm rainfall. Red represents % of total days with >100 mm and <150 mm rainfall. Green represents % of total days with >150 mm rainfall. Purple represents total counts of rainy days)

and no higher rainfall than this (Fig. 4b). Apart from this, 2010 witnessed 68 rainy days, whereas 2011 witnessed only 50, which indicates that although 2010 witnessed lesser rainfall yet due to its widespread temporal distribution, rice yield was deterred from experiencing any drastic impact.

Similarly, in WPZ the yield anomalies were very noticeable, as year 2011 witnessed higher yield compared to 2010 (Fig. 3a, b). The temperature anomalies of the two years were not that remarkable (Fig. 3a). *Kharif* season rainfall was found >20% higher in 2010 and slightly less than the zone's long-term seasonal average in 2011 (Fig. 3b). None of the years fell under the category of regional drought though year 2010 was preceded by three moderate regional droughts in the zone, i.e., 2006, 2007 and 2008 (Table 1). These droughts might have left the soil much too parched and even when 2009 received 718 mm rainfall during *kharif* season the soil could not compensate the moisture loss due to the preceding prolonged dry period. Even the study of temperature extremes estimated only <5 days of >35 °C for 2011, whereas for 2010 there were 14 days indicating warmer conditions in 2010 (Fig. 4a). Six rainfall extremes in the range of >50 mm and <100 mm and a total of 40 rainy days were recorded in 2010 and not a single rainfall extreme and a total of 64 rainy days seen in 2011 (Fig. 4b). More number of rainy days with no notable rainfall extremes and less number of extreme maximum temperature underscores the possibility of existence of *consistent soil moisture* in case of 2011 that might have supported the better rice yield in this zone. At EPZ, 14% decline in the rice yield has been noticed in 2009, whereas the very next year 2010 witnessed quantum jump to 16% in yield. In another instance, in MWZ, 5% decrease was observed in 2010, whereas a 43% increase was seen in 2011 when compared with the mean rice yield of this agro-climatic

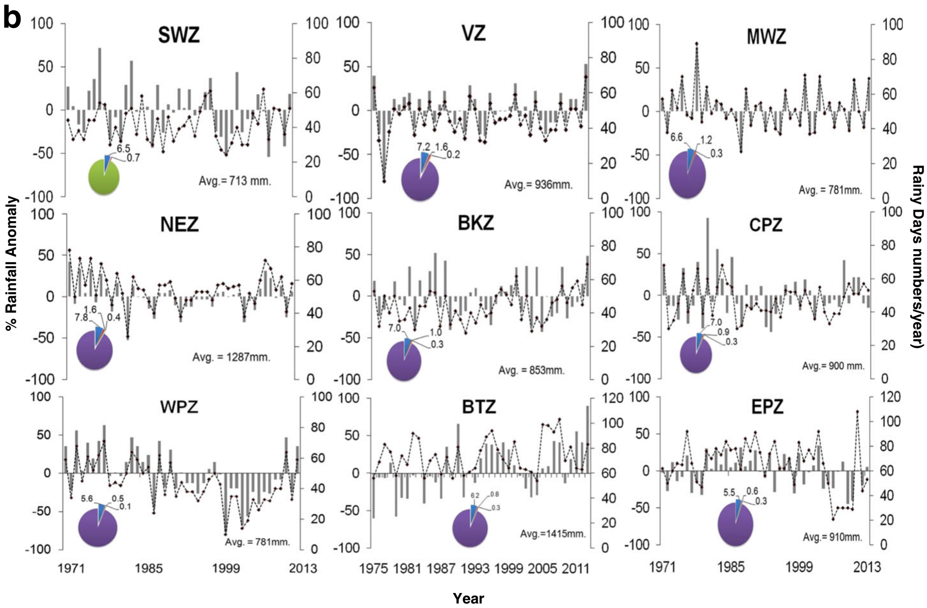

Fig 4 (continued)

zone. Similar consecutive changes (year to year) in annual yield variability were also seen in other agro-climatic zones which may most possibly be due to climatic variability, as crop variety improvement, management and other factors cannot undergo change or transformation within a short span of time.

4 Rice Growth Phase and Climate Variability

The phenological phases of rice crop like vegetative, reproductive and ripening are illustrated in the Supplementary Material file in Fig. A1 along with their respective critical temperature and rainfall requirements. Correlation at $\alpha = 0.05$ was computed to understand the relation of rainfall, maximum and minimum temperature with yield at different phenological phases (Table 3). The vegetative phase requires significant amount of water and high moisture conditions are ideal for proper growth. BKZ out of the nine zones was found to hold week negative correlation with the rainfall in all three vegetative phases. During reproductive phase, the relationship between the rainfall and the rice yield were found to be negative only in two of the zones, i.e., BKZ and CPZ, whereas the rest of the seven zones were characterized by positive correlation. As for the ripening phase, all zones were characterized by positive correlation except for VZ, BKZ and EPZ. As far as the role of temperature is concerned, rice crop generally does not suffer harsh temperature conditions due to the profuse rains of the *kharif* (monsoons) season which help it to wade off the loss that the high temperature conditions may exert upon the rice-yields. Table 3 presents a vivid record of the crop growth phase-wise relation of temperature (both temperature minimum and maximum) with that of the annual rice yield for all the zones. The analysis brought forth only a moderate estimate of the relation between the reproductive phase, temperature variability and annual rice yield, e.g., in VZ, MWZ, CPZ and WPZ. However, the reproductive phase held considerable (significant at

Table 3 Relation between Temperature, Rainfall and Rice yield in different phenological phases of Rice Crop

Agro-climatic zones	Climate parameters	RICE		
		Vegetative	Reproductive	Ripening
SWZ	Tmax	0.17	−0.06	0.05
	Tmin	0.06	0.25	−0.02
	Rainfall	0.05	0.01	0.04
VZ	Tmax	0.12	0.13	−0.06
	Tmin	0.36	0.56*	0.36
	Rainfall	−0.28	0.13	−0.26
MWZ	Tmax	0.14	0.03	0.02
	Tmin	0.32	0.53*	0.33
	Rainfall	0.12	0.05	0.07
NEZ	Tmax	−0.21	−0.16	−0.18
	Tmin	0.27	0.44	0.25
	Rainfall	0.01	0.00	0.03
BKZ	Tmax	−0.02	−0.21	−0.09
	Tmin	0.33	0.22	0.16
	Rainfall	−0.22	−0.08	−0.03
CPZ	Tmax	−0.29	−0.18	−0.36
	Tmin	0.15	0.58*	0.07
	Rainfall	−0.01	−0.01	0.01
WPZ	Tmax	0.34	0.24	0.19
	Tmin	0.56*	0.55*	0.29
	Rainfall	−0.22	0.07	0.02
BTZ	Tmax	−0.09	−0.31	−0.26
	Tmin	0.36	0.38	0.26
	Rainfall	0.22	0.19	0.03
EPZ	Tmax	−0.06	0.07	0.05
	Tmin	0.03	0.14	0.23
	Rainfall	0.16	0.00	−0.09

*Significant at $\alpha = 0.05$

$\alpha = 0.05$) relations with minimum temperature in VZ, MWZ, CPZ and WPZ, and thus resulted in decreased rice-yield with higher minimum temperature even with normal to higher rainfall in all agro-climatic zones.

Largest warming was mostly found during September in all the agro-climatic zones which could be the core reason behind the decline in the rice yield (Fig. 3a). Increase in maximum temperature may cause cellular injury, lipid membrane per-oxidation, increase rate of respiration and photosynthesis. Increase in minimum temperature may cause poor growth, decrease in photosynthesis rate which may finally culminate in adversely affecting the yield. This type of change in temperature affects the crop production through factors such as increased respiration, higher metabolism, evaporation losses and altering plant responses to biotic stresses in different agro-climatic zones of the state (Rezaei et al. 2015). Presence of clouds for prolonged period due to active southwest monsoon appeared to have reduced the incoming solar radiation, thus resulting in a significant increase in minimum temperature and negligible increase in maximum temperature (Rebetez and Beniston 1998). Increase in minimum temperature has a negative impact on rice yield overriding the impacts of radiation and maximum temperature (Nagarajan et al. 2010). Substantial reduction in rice yield is observed when high temperature was noticed during flowering period in all agro-climatic zones. Jagadish et al. (2010) also reported that rice flowering is the most sensitive stage in the face of both heat and cold stress, with the male reproductive organ determining the level of spikelet sterility.

Nevertheless, it is not alone the variability in the climatic parameters that controls the variability in yield of any crop. It is rather the complex nexus of soil, water, crop (variety) and agronomic practices along with the climate variability that modulates rice yields like in the case of other crops. So, to understand and manage the yield fluctuations it is important to have the understanding of how the various elements of this nexus interact. Therefore, continuous and rigorous studies into the field of agro-meteorology focused at impact assessment call for action plan(s) that is(are) designed in a frame of '*bottom-up approach*'. Such approaches, when implemented strategically at *'local to regional to country level'*, can prove to be the potential adaptation options capable of sustaining the rice-yields.

5 Conclusions

The study is a part of the '*bottom-up approach' as* discussed in the above section. It is of importance because it covers the Uttar Pradesh known to be the second largest state of India in terms of its rice production. The Uttar Pradesh comprises of various agro-climatic zones making it agro-meteorologically relevant to understand the observed variability in the rice yield due to the observed climatic variability.

The major findings of the above study are as follows:

a. During the rice season both minimum and maximum temperatures were found to be increasing across all the agro-climatic zones of the state, except in two zones where decreasing trends were observed.
b. Over the different agro-climatic zones, the annual minimum temperature fluctuated more than the maximum temperature, indicating the considerable change in the diurnal temperatures in this region, thereby, playing an important role in deciding the rice growth and yields.
c. Rise in minimum temperature was found to have negative impact on rice crop in the form of an average rate of decline in rice yields.
d. Furthermore, for the given study-period, the monsoon rainfalls were estimated to have a non-significant positive trend only. Moving from West to East in Uttar Pradesh, decadal rainfall trends were found to exist in a mixed manner, positive as well as negative (significant at 5% level) making it difficult to decide the overall rainfall trend pattern. Nonetheless, NEZ and VZ experienced considerably higher occurrences of rainfall extremes, whereas there was higher occurrence of rainy days in case of BTZ that raised up the annual rainfall averages.
e. The consistent and better distribution of rainy days observed in BTZ could be the reason behind higher mean yield (2 tons per hectare) when compared to the lower yields of NEZ and VZ. NEZ and VZ faced more numbers of extreme rainfall events which might have reduced the final yield. In the same place, WPZ achieved the 2 tons per hectare yield in rice despite having witnessed considerably low average annual rainfall (Fig. 4b) as well as more number of moderate drought events and even a severe drought hit in 1987 (Table 1). The farmers might have adopted well-informed agronomic practice(s) to bring up the yields given the unfavorable climatic conditions.

With the climate variability evidently affecting the crop yield, studies like the present one must be taken up at varied geographical scales preferably for eco-climatologically vulnerable regions such as for river basins (sub-basins) or for coastal strips. Assessments for such regions in the above persepective are destined to be of great use estimating the impacts of climate variability on the regional agriculture, thereby, enabling better decision-making and management at the food security front. In the twenty-first century, food security in India has to be based on the proportionate use of biotechnology, information technology and eco-technology (Swaminathan and Kesavan 2012) if the nation's population has to be fed sufficiently.

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References

Aggarwal PK, Mall RK (2002) Climate change and rice yields in diverse agro-environments of India. II. Effect of uncertainties in scenarios and crop models on impact assessment. Clim Chang 52:331–343

Ara I, Lewis M, Ostendorf B (2017) Understanding the spatially variable effects of climate change on rice yield for three ecotypes in Bangladesh, 1981–2010. ID 6287156: 1-11. doi.org/10.1155/2017/6287

AshaLatha KV, Gopinath M, Bhat ARS (2012) Impact of climate change on rain-fed agriculture in India: a case study of Dharwad. Int J Environ Sci Dev 3:368–371

Bhatta GD, Aggarwal PK (2015) Coping with weather adversity and adaptation to climatic variability: a cross-country study of small holder farmers in South Asia. Clim Dev. https://doi.org/10.1080/17565529.2015.1016883

Bhattacharya T, Panda RK (2013) Effect of climate change on rice yield at Kharagpur, West Bengal. IOSRJ Agr Vet Sci 4:6–12

Birthal PS, Negi DS, Khan Md T (2015) Is Indian agriculture becoming resilient to droughts? Evidence from rice production systems. Food Policy 56:1–12

Chao C, Guang-sheng Z, Li Z (2014) Impacts of climate change on rice yield in China from 1961 to 2010 based on provincial data. J Integ Agri 13:1555–1564

Chen C, Baethgen WE, Robertson A (2013) Contributions of individual variation in temperature, solar radiation and precipitation to crop yield in the North China plain 1961–2003. Clim Chang 116:767–788

Chung NT, Jintrawet A, Promburom P (2015) Impacts of seasonal climate variability on rice production in the central highlands of Vietnam. Agri. Agricult Sci Proced 5:83–88

Das PK, Chakraborty A, Seshasai MVR (2014) Spatial analysis of temporal trend of rainfall and rainy days during the Indian summer monsoon season using daily gridded (0.5° × 0.5°) rainfall data for the period of 1971–2005. Meteorol Appl 21:481–493

Dash SK, Jenamani RK, Kalsi SR, Panda SK (2007) Some evidence of climate change in twentieth-century India. Clim Chang 85:299–321

DES (2015) Department of Agriculture & Cooperation, Ministry of Agriculture, Government of India, New Delhi

Devkota KP, Manschadi AM, Devkota M, Lamers JPA, Ruzibaev E, Egamberdiev O, Amiri E, Vlek PLG (2013) Simulating the impact of climate change on rice phenology and grain yield in irrigated drylands of Central Asia. J Appl Meteo Clim 52:2033–2050

Dubey DP, Kumar G (2014) Trends in precipitation extremes over Central India. Mausam 65:103–108

Duncan J, Dash J, Atkinson PM (2015) Elucidating the impact of temperature variability and extremes on cereal croplands through remote sensing. Glob Change Biol 21:1541–1551

Goswami BN, Venugopal V, Sengupta D, Madhusoodanan MS, Xavier PK (2006) Increasing trend of extreme rain events over India in a warming environment. Science 314:1442–1445

Guhathakurta P, Rajeevan M (2008) Trends in the rainfall pattern over India. Int J Climatol 28:1453–1469

Guhathakurta P, Sreejith OP, Menon PA (2011) Impact of climate change on extreme rainfall events and flood risk in India. J Earth Syst Sci 120:359–373

Hatfield JL, Prueger JH (2015) Temperature extremes: effect on plant growth and development. Weather Clim Extrm 10:4–10

IMD (2012) Climate Profile of India, India, Met Monograph, Environment Meteorology-01/2010. (Eds. SD Attri and LS Rathore. India Meteorological Department New Delhi,129

IPCC (2013) Working group 1, fifth assessment report on climate change 2013: the physical science basis. Switzerland, Geneva

Jagadish SVK, Muthurajan R, Oane R, Wheeler TR, Heuer S, Bennett J, Craufurd PQ (2010) Physiological and proteomic approaches to address heat tolerance during anthesis in rice (*Oryza sativa L.*). J Exp Bot 61:143–156

Jain SK (2011) Population rise and growing water scarcity in India – revised estimates and required initiatives. Curr Sci 101:271–276

Koshal AK (2014) Changingcurrent scenario of rice-wheat system in indo-Gangetic plain region of India. Int J Sci Res Publi 4:1–13

Kothawale DR, Kumar KK, Srinivasan G (2012) Spatial asymmetry of temperature trends over India and possible role of aerosols. Theor Appl Climatol 110:63–280

Krishnan P, Ramakrishnan B, Reddy KR, Reddy VR (2011) High-temperature effects on rice growth, yield, and grain quality. In: Sparks DL (ed) Advances in Agronomy. Academic Press, Burlington, pp 87–206

Kumar KK, Sahai AK, Kumar KK, Patwardhan SK, Mishra PK, Revadekar JV, Pant GB (2006) High-resolution climate change scenarios for India for the 21st century. Curr Sci 90:334–345

Kumar NS, Aggarwal PK, Rani S, Jain S, Chauhan N (2011) Impact of climate change on crop productivity in Western Ghats, coastal and northeastern regions of India. Curr Sci 101:332–341

Liu S, Waqas MA, Wang S, Xiong X, Wan Y (2017) Effects of increased levels of atmospheric CO and high temperatures on rice growth and quality. PLoS ONE 12:e0187724. https://doi.org/10.1371/journal.pone.0187724

Lobell DB, Schlenker W, Roberts JC (2011) Climate trends and global crop production since 1980. Science 333: 616–620

Mall RK, Gupta BRD (2000) Wheat yield forecast models based on meteorological parameters. J Agrometeorol 2(1):83–87

Mall RK, Gupta BRD (2002) Comparison of evapotranspiration models. Mausam 53:119–126

Mall RK, Singh R, Gupta A, Srinivasan G, Rathore LS (2006) Impact of climate change on Indian agriculture: a review. Clim Chang 78:445–478

Mall RK, Singh N, Singh KK, Sonkar G, Gupta A (2018) Evaluating the performance of RegCM4.0 climate model for climate change impact assessment on wheat and rice crop in diverse agro-climatic zones of Uttar Pradesh, India. Clim Chang 149(3):503–515

Mittal S, Ray S (2015) What's the missing link? Reviewing climate change polices in context of Indian agricultural sector. Asian Soc Sci 11:268

MoEF (2010) Climate change and India: a 4x4 assessment a sectoral and regional analysis for 2030s. Ministry of Environment & Forests, Govt. of India, INCCA Report 2010

Mondal P, Jain M, De Fries RS, Galford GL, Small C (2015) Sensitivity of crop cover to climate variability: insights from two Indian agro-ecoregions. J Environ Manag 148:21–30

Nagarajan S, Jagadish SVK, Hariprasad AS, Thomar AK, Anand A, Aggarwal PK (2010) Local climate affects growth, yield and grain quality of aromatic and non-aromatic rice in northwestern India. Agric Ecosyst Environ 138:274–281

NAPCC (2008) National Action Plan on climate change. Government of India, New Delhi

NATCOM (2012) India: second National Communication to the United Nations framework convention on climate change-II. Ministry of environment and forests. Government of India, New Delhi

Naylor RL, Battisti DS, Vimont DJ, Falcon WP, Burke MB (2007) Assessing risks of climate variability and climate change for Indonesian rice agriculture. Proc Natl Acad Sci U S A 104:7752–7757

Oza M, Kishtawal CM (2015) Spatio-temporal changes in temperature over India. Curr Sci 109

Pai DS, Sridhar L, Badwaik MR, Rajeevan M (2015) Analysis of the daily rainfall events over India using a new long period (1901–2010) high resolution (0.25× 0.25) gridded rainfall data set. Clim Dyn:1–22

Pathak H, Pramanik P, Khanna M, Kumar A (2014) Climate change and water availability in Indian agriculture: impacts and adaptation. Indian J Agr Sci 84:671–679

Peng S, Huang J, Sheehy JE, Laza RC, Visperas RM, Zhong X, Khush GS, Cassman KG (2004) Rice yields decline with higher night temperature from global warming. Proc Natl Acad Sci U S A 101:9971–9975

Piao S, Ciais P, Huang Y, Shen Z, Peng S, Li J, Zhou L, Liu H, Ma Y, Ding Y, Friedlingstein P, Liu C, Tan K, Yu Y, Zhang T, Fang J (2010) The impacts of climate change on water resources and agriculture in China. Nature 467:43–45

Population 2016 World Bank (2016) World Development Indicators database from databank.worldbank.org/data/download/POP.pdf. Accessed 6 Feb 2019

Prasanna V (2014) Impact of monsoon rainfall on the total food-grain yield over India. J. Earth Syst Sci 123: 1129–1145

Preethi B, Ravedkar JV (2012) Kharif food grain yield and daily precipitation over India. Int J Climatol:1–9

Rani YS, Jayasree G, Sesha Sai MVR, Reddy MD (2011) Impact of climate change on rice production in Nalgonda District, Andhra Pradesh using ORYZA 2000 model. J Rice Res 4:21–26

Rao BB, Chowdhary PS, Rao VUM, Venkateswarlu B (2014) Rising minimum temperature trends over India in recent decades: implications for agricultural production. Glob Planet Change 117:1–8
Ravedkar JV, Preethi B (2012) Statistical analysis of the relationship between summer monsoon precipitation extremes and food grain yield over India. Int J Climatol:419–429
Ray DK, Gerber JS, MacDonald GK, West PC (2015) Climate variation explains a third of global crop yield variability. Nat Commun 6(5989):1–9. https://doi.org/10.1038/ncomms6989
Rebetez M, Beniston M (1998) Changes in sunshine duration are correlated with changes in daily temperature range this century: an analysis of Swiss climatological data. Geophys Res Lett 25:3611–3613
Rezaei EE, Webber H, Gaiser T, Naab J, Ewert F (2015) Heat stress in cereals: mechanisms and modelling. Eur J Agron 64:98–113
Rosenzweig C, Parry ML (1994) Potential impact of climate change on world food supply. Nature 367:133–138
Sehgal VK, Singh MR, Chaudhary A, Jain N, Pathak H (2013) Vulnerability of agriculture to climate change: district level assessment in the indo-Gangetic Plains. pp. 74. Indian Agricultural Research Institute, New Delhi
Selvaraju R (2003) Impact of El Nino-southern oscillation on Indian food grain production. Int JClimatol 23: 187–206
Singh N, Sontakke NA (2002) On climatic fluctuations and environmental changes of the indo-Gangetic Plains, India. Clim Chang 52:287–313
Singh KK, Mall RK, Singh RS, Srivastava AK (2010) Evaluation of CANEGRO sugarcane model in East Uttar Pradesh, India. J Agrometeorol 12(2):181–186
Singh S, Singh RK, Singh R (2013) Enhancing rice and wheat production by bridging yield gap in western Uttar Pradesh of India. J Wheat Res 5:43–47
Singh PK, Singh KK, Rathore LS, Baxla AK, Bhan SC, Gupta A, Gohain GB, Balasubramanian R, Singh RS, Mall RK (2016) Rice (*Oryza sativa* L.) yield gap using the CERES-rice model of climate variability for different agroclimatic zones of India. Curr Science 11:405–413
Singh N, Mall RK, Sonkar G, Singh KK, Gupta A (2018) Evaluation of RegCM4 climate model for assessment of climate change impact on crop production. Mausam 69(3):389–400
Stuecker MF, Tigchelaar M, Kantar MB (2018) Climate variability impacts on rice production in the Philippines. PLoS ONE 13: e0201426. https://doi.org/10.1371/journal.pone.0201426
Subash N, Ram Mohan HS, Sikka AK (2011) Decadal frequency and trends of extreme excess/deficit rainfall during the monsoon season over different meteorological sub-divisions of India. Hydrolog Sci J 56:1090–1109
Swaminathan MS, Kesavan PC (2012) Agricultural research in an era of climate change. Agr Res 1:3–11
Teng PPS, Caballero-Anthony M, Lassa JA (2016) The future of rice security under climate change, NTS report no. 4. Centre for Non Traditional Security Studies, Nanyang Technological University, Singapore, pp 4
van Oort PAJ, Zwart SJ (2017) Impacts of climate change on rice production in Africa and causes of simulated yield changes. Glob Change Biol 24:1029–1045
Wang P, Zhang Z, Chen Y, Wei X, Feng B, Tao F (2015) How much yield loss has been caused by extreme temperature stress to the irrigated rice production in China? Climatic Change 1-16