



Climate change impacts on rainfall and temperature in sugarcane growing Upper Gangetic Plains of India

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Abstract

Assessment of variability in climate extremes is crucial for managing their aftermath on crops. Sugarcane (*Saccharum officinarum* L.), a major C₄ crop, dominates the Upper Gangetic Plain (UGP) in India and is vulnerable to both direct and indirect effects of changes in temperature and rainfall. The present study was taken up to assess the weekly, monthly, seasonal, and annual trends of rainfall and temperature variability during the period 1956–2015 (60 years) for envisaging the probabilities of different levels of rainfall suitable for sugarcane in UGP in the present climate scenario. The analysis revealed that 87% of total annual rainfall was received during southwest monsoon months (June–September) while post-monsoon (October to February) and pre-monsoon months (March–May) accounted for only 9.4 and 3.6%, respectively. There was a decline in both monthly and annual normal rainfall during the period 1986–2015 as compared to 1956–1985, and an annual rainfall deficiency of 205.3 mm was recorded. Maximum monthly normal rainfall deficiencies of 52.8, 84.2, and 54.0 mm were recorded during the months of July, August, and September, respectively, while a minimum rainfall deficiency of 2.2 mm was observed in November. There was a decline by 196.3 mm in seasonal normal rainfall during June–September (*khariif*). The initial probability of a week going dry was higher (> 70%) from the 1st to the 25th week; however, standard meteorological weeks (SMW) 26 to 37 had more than 50% probability of going wet. The normal annual maximum temperature (T_{max}) decreased by 0.4 °C while normal annual minimum temperatures (T_{min}) increased by 0.21 °C. Analysis showed that there was an increase in frequency of drought from 1986 onwards in the zone and a monsoon rainfall deficit by about 21.25% during June–September which coincided with tillering and grand growth stage of sugarcane. The imposed drought during the growth and elongation phase is emerging as a major constraint in realizing high cane productivity in the zone. Strategies for mitigating the negative impacts of rainfall and temperature variability on sugarcane productivity through improvement in existing adaptation strategies are proposed.

1 Introduction

The Upper Gangetic Plain (UGP) zone is a large and fertile alluvial plain encompassing most of the upper plains of northern India (Dabadghao and Shankarnarayan 1973). This plain covers an approximate area of 149,000 km² and is about 550 km long in the east-west direction and nearly 380 km wide in the north-south direction, and its elevation varies from 100 to 300 m above mean sea level (Fig. 1). The UGP contains India's most densely populated areas and is one of the most

intensively farmed areas of the world (Pal et al. 2009; Mishra et al. 2013). With more than 90% irrigation and an average crop growing period of 270–300 days, all kinds of cereals, pulses, oilseeds, forages, and industrial crops are cultivated here in well-defined crop rotations making it one of the most intensively cultivated geographic units in India (Panigrahy et al. 2010; Pal et al. 2009). This zone is thus an environmentally sensitive, socially significant, and economically strategic domain of India and plays a significant role in its rural economy (Saini 2008). Sugarcane (*Saccharum officinarum* L.) is the most important industrial crop of the UGP zone, and the income of the farming community is greatly influenced by its yearly productivity, for which the annual weather is a determining factor (Glasziou et al., 1965; Mishra et al. 2013; Mali et al. 2014). It contributes about 35–40% of the total crop area (4.51 million ha) in the country (Koshal 2014). Being a part of a sub-tropical region, the climate of the UGP zone is characterized by hot summers, monsoonal rains, and cold winters

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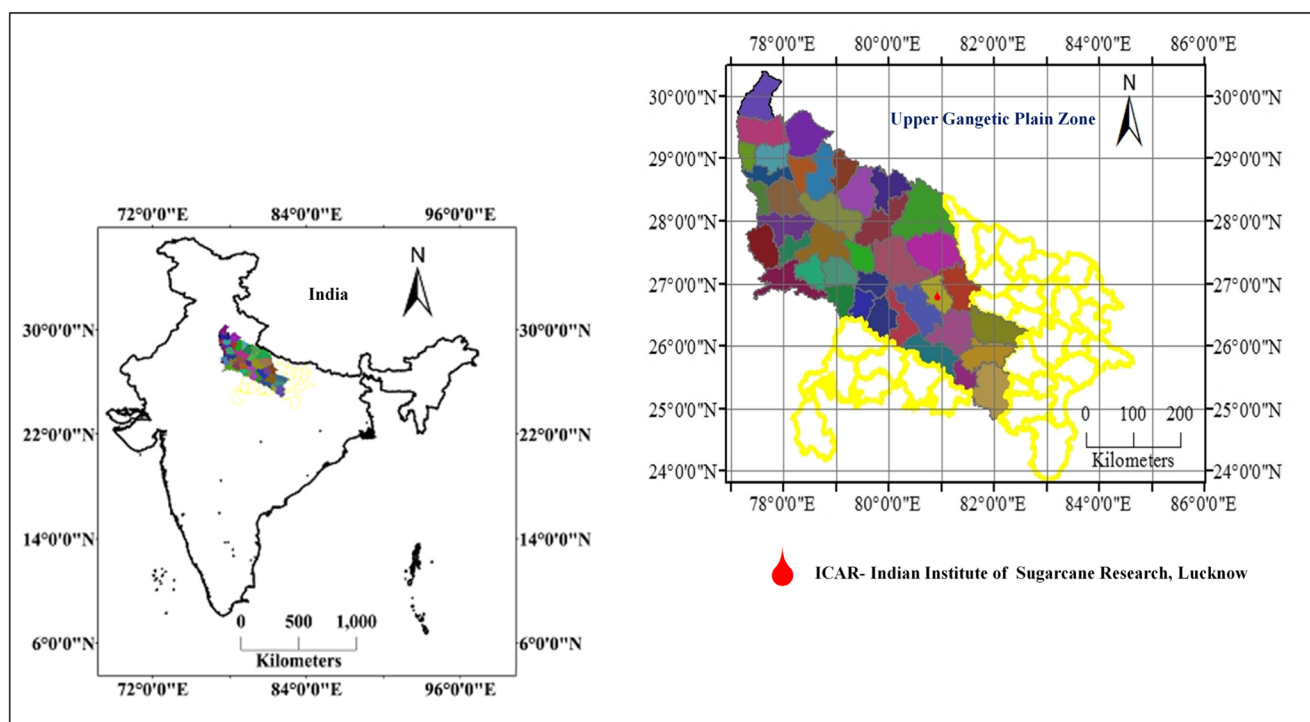


Fig. 1 Location of the study area in the Upper Gangetic Plains of India

which provides conducive weather conditions during various growth and development stages of the crop (Shrivastava et al. 2016). Being strongly connected to the tectonics and climate of the Himalayas, mild variations in these factors strongly and often adversely affect the hydrology, soil fertility, and agricultural productivity of the zone (Abrol et al. 2000; Pathak et al. 2003; Aggarwal et al. 2006; Milesi et al. 2010). Since sugarcane is a long-duration crop (12–15 months) with variable sensitivity to weather at different growth stages, even a slight departure of the weather pattern from normal (long period average) during a year is liable to cause significant loss of sugarcane and/or sugar production (Glasziou et al. 1965; Mali et al. 2014; Zhao and Li 2015). Climate change-induced variations in thermal regime, precipitation pattern, intensity, and frequency of prolonged hot summer, longer than usual rain breaks (during monsoon), heavy rains, and occurrence of frost (during winters), are being increasingly recorded for the past two decades (Shrivastava et al. 2016). It has brought wide fluctuations in sugarcane acreage and production in the zone casting fears about stability and viability of about 70 sugar mills located in the zone.

Among climatic factors, water availability and temperature regimes during the growing seasons play a major role in determining the yield and quality (sugar content) of sugarcane crop all over the world (Zhao and Li 2015). Projections about the long-term effects of global warming on the local weather of different agro-climatic regions indicate an increase in total rainfall and its capricious distribution (Panigrahy et al. 2010; Mishra et al. 2013). Several studies have indicated that global

warming could increase the precipitation by 20% with wide regional disparities ranging from deficient to excess annual rainfall (Saini 2008). Since water requirement is estimated to go up with increased temperature and an altered rainfall pattern, high water-requiring crops like sugarcane are liable to face greater adversities.

Sugarcane growth is divided into four distinct phases: germination (up to 45 days after planting—DAP), tillering (45–120 DAP), grand growth or cane elongation (120–270 DAP), and ripening or maturity (270–360 DAP), each with a specific climatic requirement (Moore and Frederik 2014). Weather variability thus has different effects on various growth processes and activities of sugarcane crop. The germination is conducive when the optimum temperature ranges between 20 and 32 °C in months of February and March (Samui et al. 2003). The tillering phase between March and June is favored when atmospheric temperatures range from 30 to 32 °C and relative humidity is about 51%. During this phase, about 12% cane weight and 15% cane height are attained. The evapotranspirational demand is very high during this period because the active growth and demand for water are met by frequent irrigation of the crop using surface water and groundwater resources. At this stage, there is little competition for available water from other crops in the zone, but concerns are being raised due to insufficient recharge of groundwater owing to the enhanced frequency of deficient rains in the recent past (Shrivastava et al. 2016). The cane elongation phase generally referred to as the grand growth phase of sugarcane spans over the months of July to September and coincides with the

monsoon season. The phase is characterized by warm temperature (28.3 °C) and high relative humidity (87%). This is the most active growth period where about 80% of cane weight is attained. Rainfall deficit in these months impacts growth adversely as there is stiff competition for irrigation water from rice and other crops, which leaves meager scope for even a lifesaving irrigation to sugarcane. A shift to a higher thermal regime brought about by lack of rains during the elongation phase also affects the dynamics of disease and pest attacks, which influences the cane and sugar yield (Bhardwaj et al. 1981; Berding and Hurney 2000). Cane growth slows down after October, and ripening begins when the temperature falls below 19.4 °C and relative humidity remains moderate (61%). The rapid buildup of sucrose and its accumulation begin in October and continue till December. Temperatures below 19 °C are conducive for sucrose accumulation, and the optimum temperature for sucrose accumulation lies between 12 and 14 °C (Fageria et al. 2010). Sucrose accumulation has been reported to decline above 26.6 °C (Clements 1980). The climate during the maturity phase influences the final sugar output which is favored under cold and dry weather with large diurnal variation in temperature and adequate soil moisture (Moore and Frederik 2014).

Analysis of the long-term weather trend by the India Meteorological Department (IMD) has revealed an increase in mean minimum temperature in all the climatic regions of India (Rathore et al. 2013). The rainfall and temperature changes in UGP may cast negative impacts on dry matter and sugar accumulation in future. Under such a scenario, shift in planting, harvesting, and cane crushing periods may be imminently required. Considering the significance of variations in rainfall and temperature on sugarcane yield and quality, the present analysis was done for deciphering the temporal rainfall and temperature variabilities during the past 60 years for developing suitable adaptation and mitigation strategies for sustainable sugarcane cultivation in the Upper Gangetic Plains of India.

2 Study area and data analysis

The Upper Gangetic Plain zone of the Indo-Gangetic Plains in India was considered in this study. The zone encompasses most of the upper plains of northern India and about 40 districts of Uttar Pradesh (Dabadghao and Shankarnarayan 1973). Studying this part for rainfall and temperature variability will thus represent majority of the sugarcane-growing districts in the zone (Fig. 1). The daily meteorological data of rainfall and temperature were recorded during the last six decades (1956–2015) at Agro-meteorological Observatory, ICAR-Indian Institute of Sugarcane Research (IISR), Lucknow. The Institute is located at 26° 80' N, 80° 94' E, 111 m above mean sea level, and the climate of the location

is characterized as semi-arid sub-tropics with cold winter and dry hot summer. The bulk of rainfall is received during June to September through the southwest monsoon, with the average being 949 mm annually. January is the coldest month, with 7.3 °C average monthly minimum temperature and 21.9 °C average monthly maximum temperature against the average monthly minimum of 26.3 °C and maximum of 39.2 °C in May which is the hottest month.

The rainfall and temperature data were compiled systematically for their climate change impact and variability assessment. The weekly, monthly, seasonal, annual, and decadal data of six decades were critically examined and statistically analyzed. Two long-period averages based on 30-year durations each were worked out to compare the long-term trends of rainfall and temperature. The year-wise drought analysis was done as “mild,” “moderate,” and “severe” on the basis of criteria suggested by IMD, Pune, India (Rathore et al. 2013). The drought classification criterion was based on departure of actual rainfall from the normal value. Rainfall declining up to 25% from normal has been termed as mild drought; rainfall decline ranging between 25 and 50% from normal rainfall has been referred to as moderate drought, and the decline ranging between 50 and 75% from normal rainfall has been termed as severe drought. Demarcation of dry and wet standard meteorological weeks (SMW) was done based on mean weekly total potential evapotranspiration by the crop at the location and a threshold value of 70% of the potential evapotranspiration (Subash et al. 2009). The probabilities of dry, wet weeks, conditional probabilities of a dry week preceded by a dry week, wet week preceded by a wet week, and consecutive two or three dry/wet weeks were calculated by the Markov chain method (Robertson 1982) at 20 mm rainfall in a given week by using the following formulae:

$$\begin{aligned}
 P(D) &= F(D)/N \\
 P(DD) &= F(DD)/F(D) \\
 P(W) &= F(W)/N \\
 P(WW) &= F(WW)/F(W) \\
 2D &= P(D_{w1}) \cdot P(DD_{w2}) \\
 3D &= P(D_{w1}) \cdot P(DD_{w2}) \cdot P(DD_{w3}) \\
 2W &= P(W_{w1}) \cdot P(WW_{w2}) \\
 3W &= P(W_{w1}) \cdot P(WW_{w2}) \cdot P(WW_{w3})
 \end{aligned}$$

where

P(D)	probability of the week being dry
P(DD)	conditional probability of a dry week preceded by a dry week
P(W)	probability of the week being wet
P(WW)	conditional probability of a wet week preceded by a wet week
F(D)	number of dry weeks
F(DD)	number of dry weeks preceded by another dry week

F(W)	number of wet weeks
F(WW)	number of wet weeks preceded by another wet week
N	number of years of data
2D, 3D	probability of two and three consecutive dry weeks, respectively, starting with the week
2W, 3W	probability of two and three consecutive wet weeks, respectively, starting with the week
P(D _{w1})	probability of the week being dry (first week)
P(DD _{w2})	probability of the second consecutive week being dry given the preceding week dry
P(DD _{w3})	probability of the third consecutive week being dry given the preceding week dry
P(W _{w1})	probability of the week being wet (first week)
P(WW _{w2})	probability of the second consecutive week being wet given the preceding week wet
P(WW _{w3})	probability of the third consecutive week being wet given the preceding week wet
w1w2w3	indicate three consecutive weeks

2.1 Assessing variability of rainfall and temperature

Mean values of different sets of observations (weekly, monthly, seasonal, annual, decadal, and normal) were compared to assess the impact of climate change on temporal rainfall and temperature variations. The coefficient of variation (CV) is a useful parameter to measure the range of variability in a data set that explains the deviation in data series from its central tendencies (Singh and Mal 2014). The coefficient of variability is found by expressing the standard deviation as a percentage of the mean value (Cheung et al. 2008). The standard deviation and coefficient of variation are calculated as

$$CV = \frac{\sigma}{\bar{x}} \times 100 \quad (1)$$

where

CV	coefficient of variation
σ	standard deviation (<i>SD</i>)
\bar{x}	mean

$$SD (\sigma) = \sqrt{\frac{\sum f (X - \bar{X})^2}{N}} \quad (2)$$

X	an observation or variate value
\bar{x}	arithmetic mean of the data
N	number of observations

3 Results and discussion

3.1 Variability in annual, decadal, and normal rainfall trends

The mean annual rainfall for the past 60 years (1956–2015) was 948.8 mm with a standard deviation of 298.6 mm and a coefficient of variation of 31.5% (Table 1). It ranged from 502.4 mm in 1993 to 2113.9 mm in 1980. During 60 years, 26 years recorded an excess rainfall while 34 years recorded a below long-term average rainfall (1956–2015, Fig. 2). The linear trend analysis of the average annual rainfall in 60 years showed a declining trend (Fig. 3). The highest mean annual rainfall (1094.7 mm) was recorded during the decade of 1966–1975 whereas the lowest average annual rainfall (748.9 mm) was recorded during the decade of 1986–1995 (Table 2). The annual rainfall pattern also showed that the frequency of mild to moderate droughts increased from 1986 onwards till 2015 (normal II) and the region faced continuous droughts except in 1988, 1991, 1996, 1998, 2008, 2009, 2011, and 2012, when the rainfall was fairly adequate (Table 3). The trends in annual and decadal rainfall variability establish that continuous failure of rainfall and increasing spells of drought are becoming increasingly precarious for sugarcane cultivation in UGP. Climate projections developed for India for the 2050s indicate a decrease in the number of rainy days by more than 15 days in western and Central India (Mall et al. 2016). As sugarcane productivity in UGP depends on total water requirement of 1500–2000 mm (Srivastava et al. 2011; Samui et al. 2014), higher or lower precipitation conditions are bound to fluctuate cane and sugar yields in the zone. Since economic conditions of farmers are highly dependent on sugarcane, in the long run, adoption of other remunerative crops like peppermint, banana, and aromatic rice could jeopardize sugar sector viability in the zone.

3.2 Seasonal rainfall variability

Seasonal analysis of rainfall variability showed that a long-term (1956–2015) highest average rainfall (825.4 mm) was received during the *kharif* season followed by *rabi* (88.8 mm) and summer seasons (34.5), which accounted for about 87, 9.4, and 3.6% of annual rainfall, respectively (Table 4). The seasonal rainfalls recorded during 1956–1985 (normal I) were 923.6, 91.5, and 36.4 mm for the *kharif*, *rabi*, and summer seasons, respectively. However, there was a marked decline in rainfall during 1986–2015 (normal II). The rainfall declined by 196.3, 5.3, and 3.7 mm during the *kharif*, *rabi*, and summer seasons, respectively, during 1986–2015 (normal II). This established that there was a decline in total rainfall in all seasons resulting in an average annual rainfall deficiency of 205.3 mm during 1986–2015 (normal II) as compared to the rainfall during 1956–1985 (normal I). The

Table 1 Monthly rainfall variability during 60 years (1956–2015) in the Upper Gangetic Plains of India

Months	Mean	Per cent	SD	CV (%)	Mean + SD	Mean - SD	Normal I rainfall (mm) (1956–1985)	Normal II rainfall (mm) (1986–2015)	Change in normal rainfall (mm)
January	16.3	1.7	19.7	120.3	36.0	-3.3	14.7	18.0	3.3
February	15.8	1.7	23.6	149.6	39.3	-7.8	11.0	20.6	9.6
March	8.0	0.8	12.9	161.2	20.9	-4.9	8.4	7.6	-0.8
April	5.4	0.6	9.4	174.4	14.7	-4.0	5.3	5.4	0.2
May	21.1	2.2	23.6	111.4	44.7	-2.4	22.6	19.7	-3.0
June	110.8	11.7	92.7	83.7	203.5	18.0	113.4	108.1	-5.3
July	264.5	27.9	129.9	49.1	394.4	134.5	290.9	238.1	-52.8
August	263.0	27.7	136.3	51.8	399.3	126.7	305.1	220.9	-84.2
September	187.2	19.7	129.7	69.3	316.9	57.5	214.2	160.2	-54.0
October	43.4	4.6	65.5	150.8	108.9	-22.1	52.8	34.0	-18.9
November	4.4	0.5	11.0	248.4	15.4	-6.6	5.5	3.3	-2.2
December	8.9	0.9	17.4	194.9	26.3	-8.5	7.5	10.4	2.9
Annual	948.8	100.0	298.6	31.5	1247.5	650.2	1051.5	846.1	-205.3

rainfall decline during the summer, *kharif*, and *rabi* seasons coincided with the germination, tillering, grand growth, and maturity phases of sugarcane. These growth phases play a key role in governing the cane and sugar yield attributes (Moore and Frederik 2014). While soil moisture below 16% has been reported to affect the germination adversely, higher rainfall leads to formation of a hard crust on the soil surface and hampers the germination process. Rainfall at the time of planting has adverse effects on germination of cane setts (Binbol et al. 2006) as dry weather is favorable for germination (Jika 1997). Kumar (1984) reported a yield decline in sugarcane due to rainfall during the germination phase. Summer season (March to May) rainfall amounting to 32.7 mm shall be helpful for inter-culture operations during the tillering phase, but

rainfall decline during grand growth and maturity phases might become a major bottleneck for cane and sugar production in UGP affecting both farmers and mills in the zone (Shrivastava et al. 2016). Several authors have reported the effect of rainfall on cane production (Shrivastava 2012; Kumar et al. 2011; Ramulu 1996). The tillering phase however is favored by rainfall (23.5 mm), where underground branching from compact nodal joints of primary shoot occurs for providing the crop with appropriate an number of stalks required for good yield. Under rainfall deficit conditions, tillering gets retarded and affects the final yields adversely (Mall et al. 2016). Sugarcane productivity in the zone thus requires sustenance by surface rainwater harvesting or moisture conservation through in situ management or ex situ water conservation

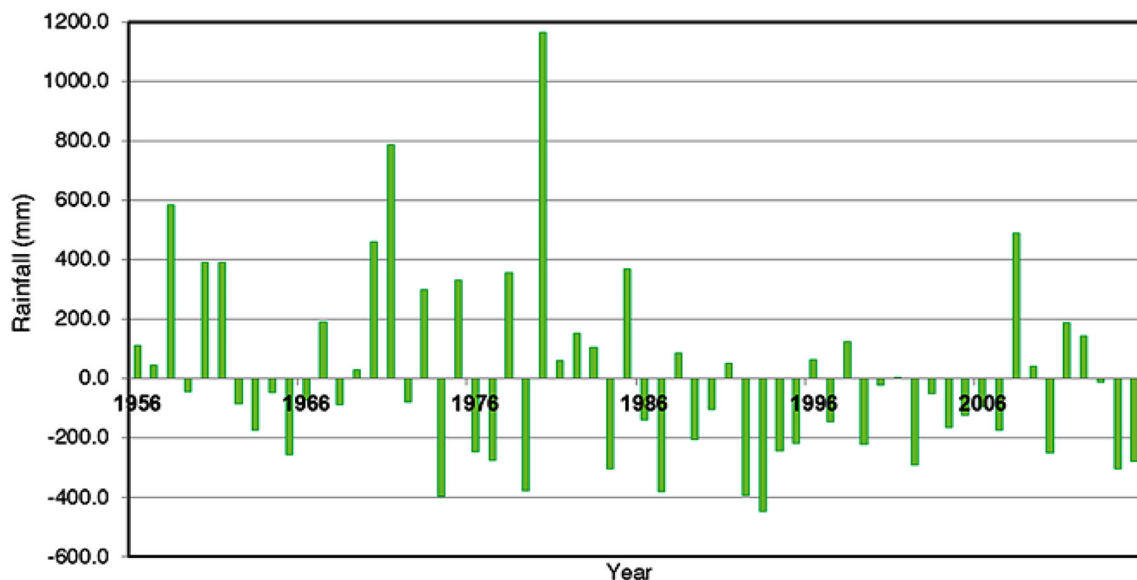
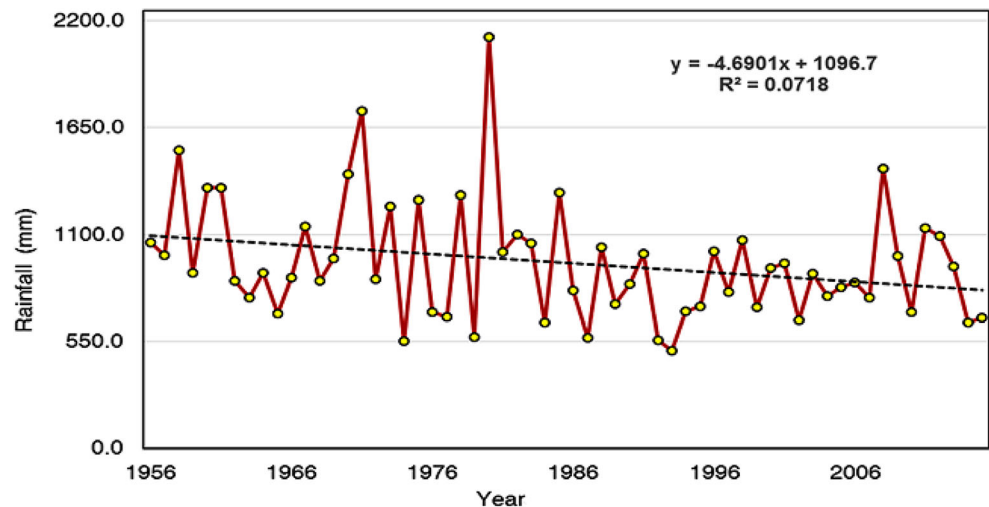


Fig. 2 Decade-wise annual rainfall variability in the Upper Gangetic Plains of India during 1956–2015 Horizontal axis indicates year and vertical axis represents mean annual rainfall (mm)

Fig. 3 Decade-wise annual rainfall trend in the Upper Gangetic Plains of India during 1956–2015 Horizontal axis indicates year and vertical axis represents mean annual rainfall (mm)



practices for enabling appropriate germination, tillering, elongation, and ripening for profitable sugarcane cultivation in UGP.

3.3 Monthly rainfall variability

The assured rainfalls during June, July, August, and September was 110.8, 264.5, 263.0, and 187.2 mm, with standard deviations of 11.7, 27.9, 27.7, and 19.7, respectively (Table 4, Fig. 4). Out of four rainy months, July and August contributed 27.9 and 27.7% to the total annual rainfall and both months together contributed about 55.6% in total annual rainfall and 63.9% in total monsoon rainfall (Table 1). June and September months contributed 11.7 and 19.7% in total annual rainfall and 13.4 and 22.7% in monsoon rainfall, respectively. The contribution of November (0.5%), December (0.9%), January (1.7%), February (1.7%), March (0.8%), and April (0.6%) was merely 6.2% in the long-term (1956–2015)

average annual rainfall of 948.8 mm with high coefficient variability. The decline in rainfall was observed in monthly rainfall normal (1985–2015) in all the months starting from March to November, whereas increased rainfall was observed in the months of January, February, and December as compared to the monthly rainfall normal of 1956–1985. Though the climate change impact on monthly rainfall was realized in all the months during 1986–2015 (normal II), a maximum decline in rainfall occurred in the months of July (52.8 mm), August (84.2 mm), and September (54 mm). The declining trends of rainfall during July, August, and September project adverse impacts on the grand growth phase which starts after 120 days of planting and lasts up to 250–270 days in sugarcane (Mall et al. 2016). It is the most crucial phase wherein actual cane formation, dry matter accumulation, elongation, and thus yield buildup takes place. Samui et al. (2003) reported a significant increase in cane yields due to the higher amount of rainfall during the grand growth stage in the same

Table 2 Decadal variability in rainfall pattern during 60 years (1956 to 2015) in the Upper Gangetic Plains of India

Months	1956–1965 Rainfall (mm)	1966–1975	1976–1985	1986–1995	1996–2005	2006–2015
January	21.6	6.99	15.5	11.6	26.7	15.6
February	5.7	11.55	15.6	15.5	13.4	32.8
March	8.4	7.56	9.4	5.6	4.2	13.0
April	4.8	4.6	6.5	2.2	4.2	9.9
May	25.9	28.47	13.5	14.3	22.7	22.0
June	55.0	152.33	133.0	94.9	119.9	109.6
July	278.2	287.73	306.7	203.2	241.3	269.7
August	322.1	345.27	247.9	204.7	206.4	251.5
September	188.6	204.89	249.2	152.3	164.0	164.3
October	94.7	28.35	35.4	29.8	43.1	29.0
November	1.6	6.44	8.6	1.9	6.1	1.9
December	4.4	10.47	7.6	12.7	14.3	4.0
Annual	1011.1	1094.7	1048.7	748.9	866.2	923.4

Table 3 Annual drought frequency during 60 years (1956 to 2015) in the Upper Gangetic Plains of India

Year	Rainfall (mm)	Category	Year	Rainfall (mm)	Category	Year	Rainfall (mm)	Category	Year	Rainfall (mm)	Category
1956	1059.7	Normal	1971	1736.0	Normal	1986	809.6	Mild drought	2001	952.6	Mild drought
1957	992.1	Normal	1972	870.9	Mild drought	1987	567.8	Moderate	2002	656.8	Moderate
1958	1240.5	Normal	1973	1246.2	Normal	1988	1036.1	Normal	2003	899.8	Mild drought
1959	908.6	Mild drought	1974	551.1	Moderate	1989	741.4	Mild drought	2004	784.3	Mild drought
1960	1338.7	Normal	1975	1279.1	Normal	1990	844.4	Mild drought	2005	826.5	Mild drought
1961	1339.4	Normal	1976	701.1	Moderate	1991	999.3	Normal	2006	854.5	Mild drought
1962	862.8	Mild drought	1977	674.5	Moderate	1992	554.1	Moderate	2007	775.7	Mild drought
1963	774.7	Mild drought	1978	1303.1	Normal	1993	502.4	Moderate	2008	1437.9	Normal
1964	902.9	Mild drought	1979	572.2	Moderate	1994	704.9	Moderate	2009	990.6	Normal
1965	692	Moderate	1980	2113.9	Normal	1995	728.8	Mild drought	2010	698.6	Moderate
1966	876.6	Mild drought	1981	1008.4	Normal	1996	1013.8	Normal	2011	1134.8	Normal
1967	1140.2	Normal	1982	1100.2	Normal	1997	801.8	Mild drought	2012	1092.4	Normal
1968	859.7	Mild drought	1983	1053	Normal	1998	1071.6	Normal	2013	934.8	Mild drought
1969	976.3	Normal	1984	644.9	Moderate	1999	726.6	Mild drought	2014	644.8	Moderate
1970	1410.4	Normal	1985	1315.5	Normal	2000	928.2	Mild drought	2015	669.4	Moderate

study zone. Any alteration in rainfall can thus impact the water balance of crop at a specific stage and affect the plant phenology and cane and sugar yields (Horikoshi and Fisch 2007).

Decline in rainfall in the months of October, November, and December during 1986–2015 (normal II) by 18.9, 2.2, and 2.9 mm was recorded against normal I (Table 1). The mean monthly average of rainfall in October, November, and December was 43.4, 4.4, and 8.9 mm with coefficients of variation of 150.8, 248.4, and 194.9. During these months, the ripening phase of sugarcane crop prevails and lasts for about 250–360 days after planting, where rapid sucrose accumulation takes place and vegetative growth gets retarded. The expanse of phase covers both post-monsoon and winter seasons. This phase of crop growth demands colder and drier conditions than the grand growth phase to undergo sufficient disaccharide formation. Cardozo (2012) reported a temporary setback to sucrose accumulation due to copious rainfall during these months. Our study indicates that the ripening phase of sugarcane during 1986–2015 (normal II) in the zone suffered from severe rainfall deficit. The adverse effects however might have been curtailed partially through adequate irrigation

supplement or conserved soil moisture from the preceding GGP rainfall.

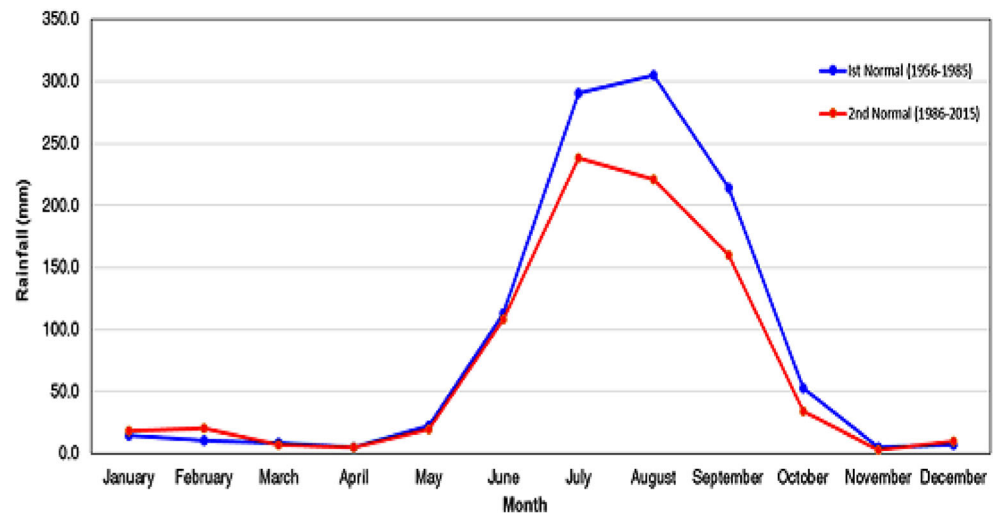
3.4 Weekly rainfall variability, initial and conditional probability of wet and dry weeks

Mean weekly rainfall during the second normal (1986–2015) declined for 29 SMWs, remained the same for 2 SMW, and increased for 21 SMWs as compared to that of the first normal (1956–1985). The maximum decline in mean weekly rainfall (–52.7 mm) was recorded in the 32nd SMW, and the maximum increase (8.4 mm) was in the 36th SMW. During the second normal, there was a continuous deficit in mean weekly rainfall from the 26th to the 41st SMW, except for the 33rd, 36th, and 38th SMW. The period (end of June to mid-October) coincides with the rainy season crucial for sugarcane elongation in the zone. Deficit in rainfall during this period casts adverse impacts on sugarcane biomass accumulation and cane and sugar yield. The trend indicates delay in the onset of monsoon and also moisture deficit during the critical cane elongation phase. This necessitates adoption of techniques to ensure adequate

Table 4 Seasonal rainfall variability rainfall pattern during 60 years (1956 to 2015) in the Upper Gangetic Plains in India

Season	Average rainfall (mm)	Per cent	SD	CV (%)	Normal I (1956–1985) rainfall (mm)	Normal II (1986–2015) rainfall (mm)	Change in normal rainfall (mm)
Summer or pre-monsoon (March–May)	34.5	3.6	8.5	24.5	36.4	32.7	–3.7
Monsoon or <i>kharif</i> (June–September)	825.4	87.0	125.4	15.2	923.6	727.3	–196.3
Winter or <i>rabi</i> (October–February)	88.8	9.4	23.4	26.4	91.5	86.2	–5.3
Annual	948.8	100.0	128.5	13.5	1051.5	846.2	–205.3

Fig. 4 Month-wise mean rainfall variability trend in the Upper Gangetic Plains of India during 1956–2015. Horizontal axis indicates month and vertical axis represents mean annual rainfall (mm)



moisture availability during this period. The weekly rainfall probability and pattern of deficit and surplus rainfall information are very useful for suitable crop planning including decisions about pre-sowing irrigation, time of planting, inter-culture, irrigation scheduling, fertilizer application, and use of plant protection chemicals. This information is also required for scheduling of cane harvest and raising of ratoon crop to obtain optimum sugar recovery. In addition, efficient use of rainwater largely depends on prior knowledge about the weather for getting maximum production (Srivastava et al. 2011).

The weekly initial wet probability $P(W)$ and conditional wet probability of rainfall $P(W/W)$ were determined by using the Markov chain model. The data revealed probability of standard meteorological weeks (SMW) 1–25 going dry was higher. The analysis revealed occurrence of 70% of initial probability of a dry week from the 1st to the 25th week in the zone (Fig. 5). These SMWs covered the germination and tillering phases of sugarcane and suggested greater relevance of external water application for sustaining the plant population of crop which determines the final crop stand. Considering the probability of drier SMWs and low water application efficiency under largely adopted flood irrigation in UGP, there is a need for adoption of efficient irrigation methods like surface and sub-surface drip, use of gated pipes, and skip furrow irrigation (Srivastava et al. 2011). Also, micro-irrigation methods like surface and sub-surface irrigations shall be more amenable to fertigation which enhances the nutrient use efficiency. The initial and conditional probabilities of getting 20 mm rainfall were more than 50% during the 26th to the 37th week. A high probability (> 60%) of going wet existed between SMWs of 26 and 37. The mean weekly rainfall during the 26th to the 37th SMW varied from 37.6 to 69.6 mm. The mean weekly rainfall showed that the 26th to 37th SMWs were the most stable period for rainfall in UGP (Fig. 5). Expected 65.0% rainfall to the total average of annual

rainfall was received during the 26th to 37th SMWs (25th June to 16th September). The collection of surface runoff water during this excess rainfall period and its recycling for agricultural use during the subsequent dry period shall serve to reduce soil, water, and nutrient losses from the agricultural crop fields grown in the zone. The conditional probability of a wet week preceded by a wet week was also high from the 25th to 36th weeks. Straddling with the end of the tillering and grand growth phases, these SMWs coincide with onset of a southwest monsoon in the zone. But an increasing trend of delayed-onset, frequent, and longer monsoon breaks in SMWs 26–37 has led to excessive tiller mortality, poor growth of surviving tillers, and cane yield decline in the zone. Further, these SMWs also overlap with transplanting of rice, which is a fierce competitor for available water and therefore leaves little chance for irrigation of sugarcane (Pathak et al. 2014; Rezaei et al. 2015).

It is well known that uptake of nutrients by sugarcane crop is maximum during the late tillering phase, and any paucity of water at this stage causes poor nutrient availability to plants and hampers the crop growth (Lobell and Gourdjji 2012; Pathak et al. 2014). This scenario further compels to go for adoption of more efficient irrigation methods (Bhaskaran and Nair 2014). However, the conditional probability of two consecutive weeks going wet ranged from 33 to 87% during 24–39 SMWs which suggests that even with no irrigation supplement during this period, the crop can sustain itself though with low productivity. The weekly rainfall of 20 mm or more with 70% probability was recorded during the 33rd and 34th SMWs. The probability of occurrence by more than 30% of getting 20-mm rainfall for two consecutive wet weeks is from the 22nd to 39th weeks (Fig. 6), but it varied in case of occurrence of three consecutive weeks and was never above 58% even during the peak season of the southwest monsoon (July and August). The very high probability of SMWs 42–52

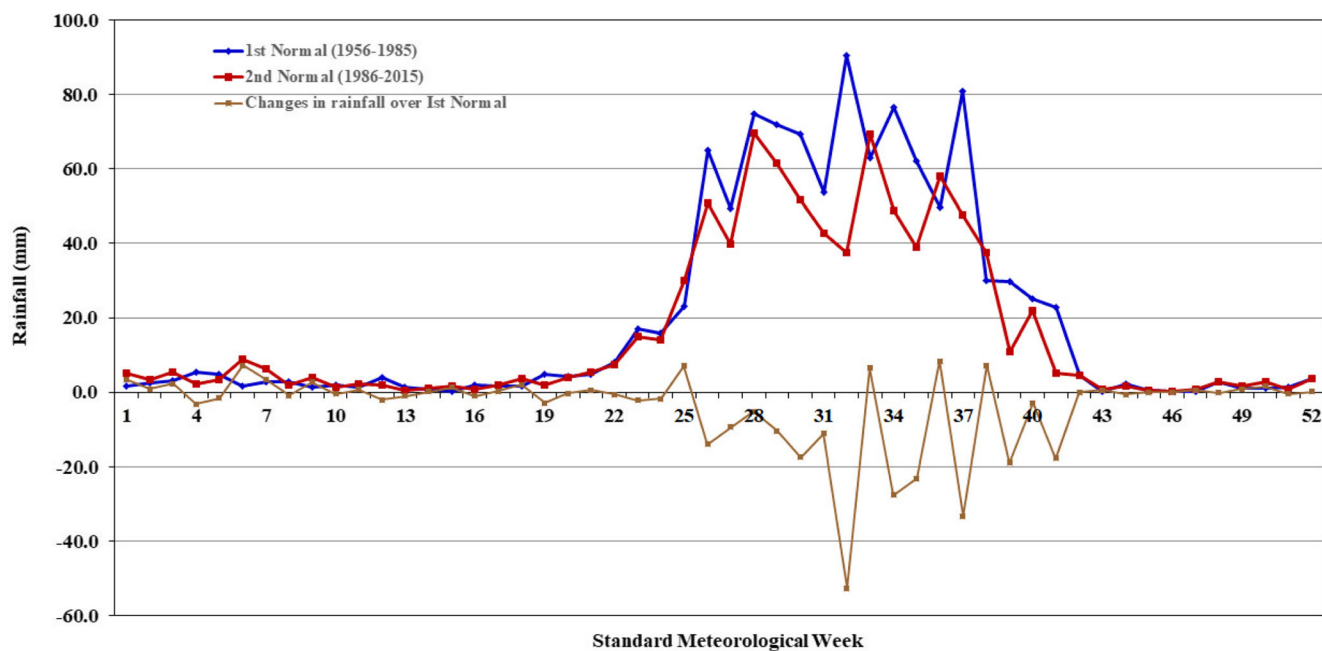


Fig. 5 Variability in average weekly rainfall for I normal (1956–1985) and II normal (1986–2015) in the Upper Gangetic Plains of India. Horizontal axis indicates standard meteorological week and vertical axis represents mean annual rainfall (mm)

going dry indicated moisture scarcity during the ripening phase and suggests the requirement of irrigation to sustain growth and sugar accumulation (Fageria et al. 2010).

3.5 Normal temperature variability

Based on 60-year (1956–2015) temperature data, the annual mean maximum temperature (T_{max}) was 31.4 °C and the annual mean minimum temperature (T_{min}) was 18.1 °C (Tables 5 and 6). However, the mean maximum temperature varied from 21.9 to 39.2 °C, the lowest being in January and the highest in May. Monthly variation in mean minimum temperature ranged from 7.3 °C in January to 26.3 °C in June. Comparison of two 30-year normal annual maximum temperatures revealed a decline by 0.4 °C and a rise by 0.21 °C in annual mean minimum temperature during the latter period (1986–2015). The findings are in agreement with the IMD report on a rising trend of annual minimum temperature and a decline in annual maximum temperature levels in various agro-climatic zones of India (Rathore et al. 2013). Change in normal T_{max} for different months shows the highest decline in January (−2.0 °C), May (−0.9 °C), and June (−0.8 °C) whereas the monthly T_{max} recorded an increase in July, August, and September. This increased T_{max} coincided with a significant decline in rainfall during the monsoon season, when sugarcane crop is spanning through the grand growth stage. Change in T_{min} was evident with rising levels ranging from 0.22 °C in May to 0.7 °C in February. Further, a continuous increase in T_{min} during May to September starting from

0.22 °C and reaching 0.47 °C can be linked with reduced rains during summer and monsoon months.

Analysis of change in mean T_{max} and T_{min} for standard meteorological weeks (SMW) for two long-period averages indicated a net decline in T_{max} for 38 SMWs and a rise during 10 SMWs with no change for the remaining 4 weeks (Fig. 7a, b). Similarly, T_{min} increased in 37 SMWs and declined in 14 with one SMW remaining unchanged. Although decline in T_{max} and rise in T_{min} during different SMWs do not exactly correspond to each other, net reduction in T_{max} coupled with rising T_{min} during SMWs 5–13 coincided with the main sugarcane planting season (spring planting) in the zone. The rise in both during SMWs 29–41, wherein cane elongation takes place, makes it essential to explore and adopt suitable adaptation measures. A decline in T_{max} and an increase in T_{min} again during SMWs 45–52 would effectively reduce the diurnal temperature variation needed for adequate sugar accumulation; hence, protection measures are required to be taken here too (Gawander 2007).

3.6 Adaptation strategies for sugarcane crop

A broader outline of change in rainfall and temperature regimes during the past six decades in the Upper Gangetic Plain zone of India puts forward an overall reduction in rains during the summer, monsoon, and winter seasons of the year. There was a 19.52% decline in average annual rainfall with the highest decline during monsoon. Change in weekly temperature revealed three major trends: (a) reduction in mean weekly T_{max} during the spring season (February–March)

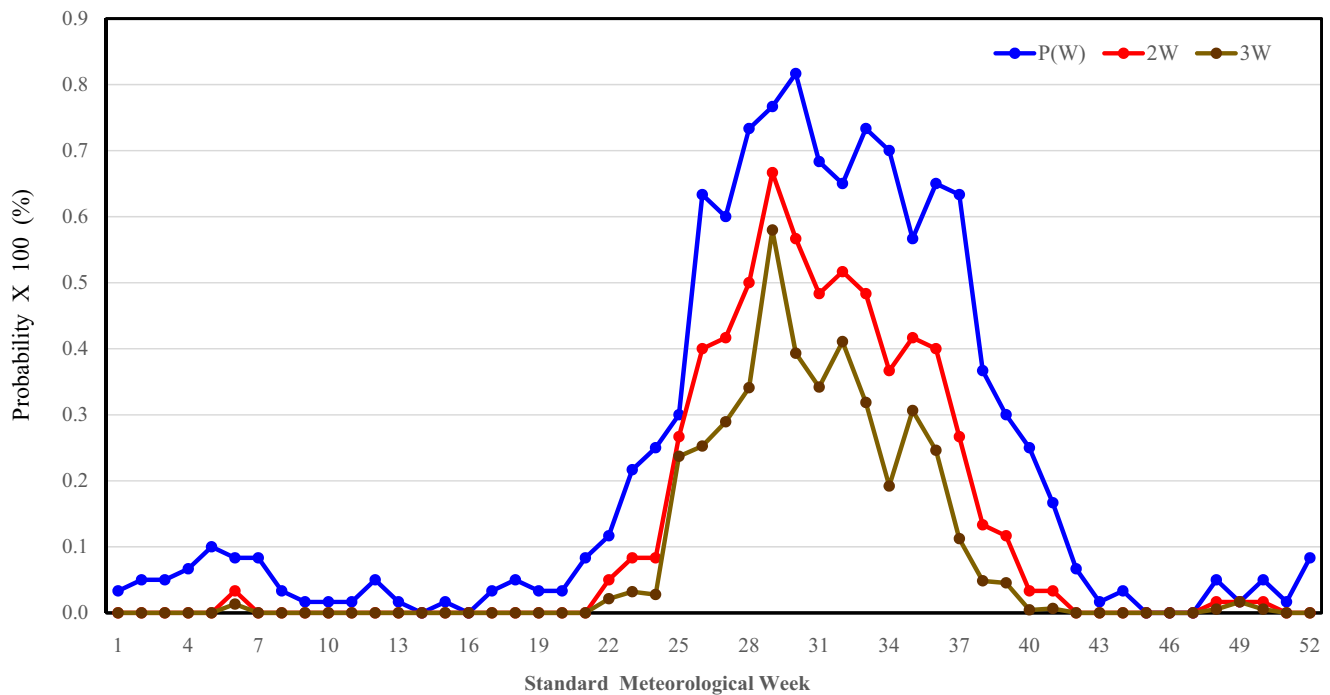


Fig. 6 Initial and conditional probabilities of rainfall in the Upper Gangetic Plains of India during 1956–2015. Horizontal axis indicates standard meteorological week and vertical axis represents probability

(%), PW: probability of wet week; 2W: probability of two consecutive wet weeks; 3W: probability of three consecutive wet weeks

coupled with rising mean weekly Tmin, (b) increase in both mean weekly Tmax and Tmin during the monsoon season (mid-June to end of September), and (c) increase in mean weekly Tmin during the winter season (November–December). These trends when related with growth stages of sugarcane and probability of weeks going dry or wet ascertain that the recommended time of sugarcane planting between 15th February and 15th March still holds good for the Upper

Gangetic Plain zone. This is explained to be due to the prevailing average mean weekly temperature ranging between 18.1 and 25.8 °C during the period, which is conducive for sugarcane bud sprouting and emergence (Shrivastava et al. 2016). Also, high probability of these weeks going dry suggests that there will be no rain hindrance during the germination phase. Increased Tmin during the period, however, may cause higher soil moisture loss through evaporation which

Table 5 Monthly maximum temperature (°C) variability during 60 years (1956–2015) in the Upper Gangetic Plains of India

Month	Mean temperature (°C)	SD	CV (%)	Normal I Tmax (°C) (1956–1985)	Normal II Tmax (°C) (1986–2015)	Change in normal Tmax (°C)
January	21.9	2.9	13.3	22.9	20.9	–2.0
February	25.4	1.8	7.1	25.6	25.3	–0.3
March	31.3	1.7	5.5	31.7	30.9	–0.7
April	37.0	3.2	8.8	37.5	36.5	–0.9
May	39.2	2.1	5.4	39.6	38.8	–0.8
June	37.8	2.7	7.2	37.8	37.8	–0.1
July	33.6	1.2	3.6	33.5	33.7	0.2
August	33.0	1.5	4.5	32.6	33.3	0.7
September	32.8	1.1	3.4	32.8	32.8	0.1
October	32.2	2.3	7.1	32.3	32.1	–0.2
November	28.5	1.5	5.1	28.5	28.6	0.1
December	23.9	1.3	5.4	24.1	23.6	–0.5
Annual	31.4	0.7	2.3	31.6	31.2	–0.4

Table 6 Monthly minimum temperature (°C) variability during 60 years (1956–2015) in the Upper Gangetic Plains of India

Month	Mean	SD	CV (%)	Normal I Tmin (°C) (1956–1985)	Normal II Tmin (°C) (1986–2015)	Change in normal Tmin (°C)
January	7.3	1.4	19.5	7.3	7.3	–0.02
February	10.4	1.9	18.8	10.0	10.7	0.70
March	14.7	1.2	8.2	14.4	15.0	0.63
April	20.4	1.2	5.8	20.5	20.3	–0.22
May	24.5	1.3	5.2	24.4	24.6	0.22
June	26.3	1.9	7.1	26.2	26.5	0.26
July	25.9	1.9	7.2	25.8	26.0	0.25
August	25.5	0.7	2.9	25.3	25.6	0.31
September	24.0	1.2	5.0	23.8	24.3	0.47
October	18.5	1.5	7.9	18.6	18.5	–0.12
November	11.9	1.8	15.5	11.7	12.0	0.32
December	8.0	2.6	32.3	8.1	7.9	–0.26
Annual	18.1	0.7	4.0	18.0	18.2	0.21

may necessitate one or two additional light irrigations during the germination phase.

Decline in mean weekly Tmax and rise in mean weekly Tmin during most weeks of the summer months (April–June) tend to remain conducive for the tillering phase, provided adequate soil moisture is maintained. Water scarcity during this period is emerging as a major threat to sugarcane cultivation in view of drying aquifers and declining rainfall. Water management practices like drip irrigation and mulching of inter-row spaces with sugarcane trash (Srivastava et al. 2011; Shrivastava et al. 2011) may be resorted to under such situations. The number of millable canes formed during the cane elongation phase (monsoon season) determines the cane productivity per unit area (Moore and Frederik 2014). The weather condition during this phase is thus crucial for survival of tillers and their progression to millable canes (Shrivastava et al. 2016). Changes in rainfall and temperature regimes during this phase reveal a decline in rainfall by 196.3 mm, an increase in both mean weekly Tmax and Tmin, and more probability of early withdrawal of monsoon as indicated by poor probability of a wet week from the 37th SMW onwards. This indicates that there is lesser availability of water and higher evapotranspirational loss which would lead to high tiller mortality and poor cane elongation causing cane and sugar yield losses. Considering this, sugarcane planting in deep trenches (widely spaced) leading to deeper root penetration, increased water and nutrient foraging capacity, and amenability to drip fertigation needs to be widely adopted and promoted (Srivastava and Verma 2017). Serious efforts are also needed to increase groundwater recharging and surface water harvesting to provide irrigation during the end of the rainy season.

Sugar accumulation in cane gets accelerated on the 42nd SMW (mid-October) onwards and continues till the subsequent year's 7th SMW (middle of February) in sugarcane crops cultivated in the Upper Gangetic Plain zone. The

declining mean weekly Tmax and rising mean weekly Tmin along with declined rainfall are likely to affect sucrose accumulation processes adversely and reduce sugar yields (Glasziou et al. 1965). This is explained to be due to narrowed diurnal temperature variation and Tmin slipping below 10 °C during SMW 48 to the subsequent year's 8th SMW (mid-February), which causes reduced sugar recovery after crushing. It is well known that a wider diurnal temperature variation during the maturity phase of sugarcane is conducive for sugar accumulation and minimum temperature below 10 °C diverts sugar for organic acid formation (Shrivastava et al. 2016). The situation thus needs to be tackled by developing climate-resilient sugarcane varieties as the sugar accumulation process is largely controlled by the genetic making of the variety grown in a particular region.

4 Conclusion

Assessing the effect of climate change on weather variability and their impacts on crop growth is an important prerequisite for sustaining crop productivity in the near future. Sugarcane growth phases are influenced by rainfall, temperature, relative humidity, evaporation, and sunshine. As rainfall and temperature are the most crucial weather parameters that govern sugarcane productivity, the present study analyzes the effect of climate change on annual rainfall and temperature variability for a period of 60 years in the Upper Gangetic Plain zone in India. Inclusion of other weather parameters would have made the study more illustrative; however, realizing the complex interactive influences and the interest of clarity on impacts of rainfall and temperature variability on sugarcane growth, other parameters were not included. The rainfall and temperature variability clearly brought forth the changes in climate, and there has been a decline in rainfall by 205.3 mm during

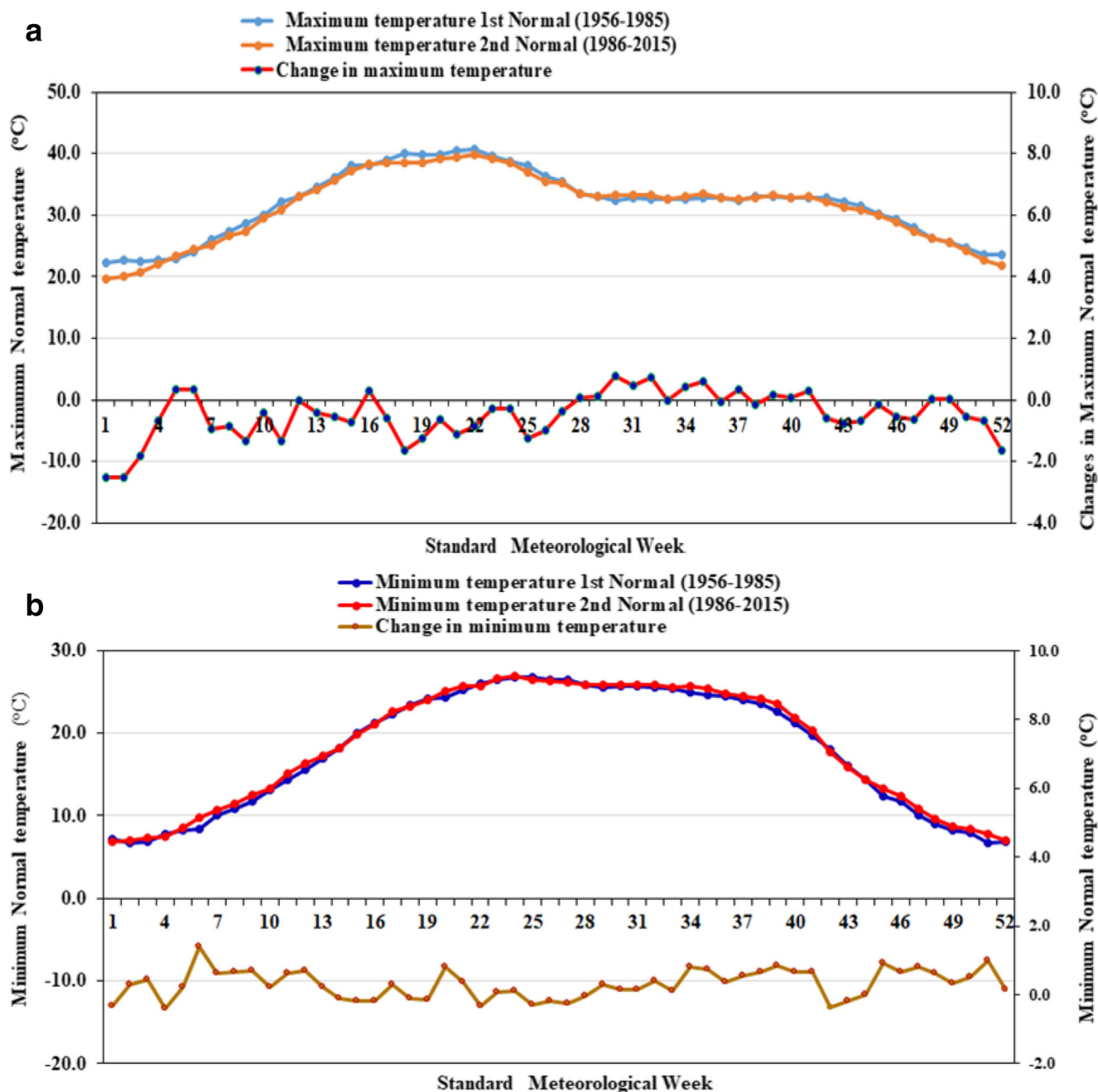


Fig. 7 a Variation between mean maximum weekly temperature (°C) for I normal (1956–1985) and II normal (1986–2015) in the Upper Gangetic Plains of India. Horizontal axis indicates standard meteorological week and vertical axis represents temperature (°C). **b** Variation between mean

minimum weekly temperature (°C) for I normal (1956–1985) and II normal (1986–2015) in the Upper Gangetic Plains in India. Horizontal axis indicates standard meteorological week and vertical axis represents temperature (°C)

1986–2015 against 1956–1985. Mean annual Tmax decreased by 0.4 °C while an increase in mean annual Tmin by 0.21 °C was recorded for the corresponding period. A fare degree of variation has also been recorded in the weekly rainfall and temperature conditions of the zone. A maximum rainfall deficit of 21.25% in monsoon rains was recorded between July and September which coincided with the most critical growth stage of sugarcane. A significant increase in temperature during the cane elongation phase was followed by a non-

conductive temperature change during the ripening phase. Climate change therefore potentially impacts sugarcane productivity in UGP which necessitates alterations in agronomic management of the crop. Adaptation measures like development of climate-resilient sugarcane varieties, sugarcane planting in widely spaced deep trenches, mulching of inter-row spaces with trash, drip irrigation, and fertigation are proposed to mitigate the climate change impact. Groundwater recharging and surface water harvesting to provide irrigation

during the tillering and elongation phases of sugarcane are of immediate importance for sustaining sugarcane farming in the Upper Gangetic Plain zone of India. Studies on sugarcane growth and yield amidst intensive farming-induced changes in soil fertility status under the changing climate, disease, and pest scenario would make an important future research priority in the intensively cultivated UGP zone in India.

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