



Weather variability trends in Gangetic plains of Uttar Pradesh, India: influence on cropping systems and adaptation strategies

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Abstract

Weather variability over the long run exhibits the trends of change in climate and forewarns for development and deployment of adaptation measures. Gangetic plain of Uttar Pradesh in India is an agriculturally important geographical region of South East Asia. The region is vulnerable to weather variability led glacier melting, climate change impacts and increased competition for land. In addition, changes in rainfall, groundwater and weather patterns are deteriorating the agricultural and water systems that are bound to affect the food production and throw the poor populace into chaotic conditions. As weather variability trends are being increasingly used for sustaining the food production in climate-sensitive regions, the present study was taken up in Lucknow district of Uttar Pradesh. Daily meteorological datasets of temperature, rainfall, rainy days, evaporation, wind speed, relative humidity and bright sunshine hours during the past 63 years (1956–2018) were analysed for long-term trends. The study indicated conspicuous long-term trends of reduction in annual rainfall ($-28.97 \text{ mm decade}^{-1}$), rising level of daily Tmin ($0.09 \text{ }^\circ\text{C a decade}$) and RH ($1.08\% \text{ decade}^{-1}$) coupled with significant declining trends in evaporation ($-0.31 \text{ mm day}^{-1}$), wind speed (-0.29 km h^{-1}) and bright sunshine hours (-0.19 h day^{-1}), that poignantly elucidates a clear warming trend over the period in the region. Multi-pronged adaptation strategies comprising of development of water efficient crop varieties, cropping system diversification with less water requiring crops, adoption of water efficient irrigation techniques, surface water harvesting and copious ground water recharge have been proposed for coping up.

Keywords Weather trend analysis · Gangetic plains · Staple food crops · Sugarcane · Adaptation strategies

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1 Introduction

The Indo-Gangetic Plain (IGP), stretched across 2.5 million km², in the northern South East Asia, is highly unshielded and vulnerable to the impacts of global warming (Hijioka et al., 2014). The continued warming has translated into specific impacts on biodiversity changes, soil health, water scarcity, heat and cold induced plant mortality, vegetation cover and crop yields (Leng & Huang, 2017). Chattopadhyay et al. (2019) reported that temperature and rainfall were the two largest climatic causes for crop yield variations and are expected to dominate food security in different agro-climatic zones of India. This is supported by Ray et al. (2019), who assessed the impact of mean climate change on per cent yield of top ten global crops *vis a vis* barley, cassava, maize, oil palm, rapeseed, rice, sorghum, soybean, sugarcane and wheat crops to be -7.9%, -0.5%, -13.4%, 0.5%, -0.3%, 2.1%, 3.5%, 1.0% and -0.9%, respectively. Hijioka et al. (2014) projected changes in intensity of heat waves, temperatures, rainfall in this region and proclaimed them to be further compounded by low resilience and adaptive capacity of the agrarian societies. Poudel and Shaw (2016) observed an increase in temperature of approximately 0.02–0.07 °C per year in different seasons and a mixed trend in precipitation in Nepal, a landlocked nation in South East Asia containing some parts of IGP. A widespread rise in temperatures was recorded in Indo-Pacific region in 1971–2005, while rise and fall in temperatures have been recorded in Chinese delta (Caesar et al., 2011; Lu et al., 2016; Yin et al., 2016). Though accounted for by IPCC (2013) that IGP will be adversely affected by temperature rise, substantial reduction in rainfall and water stress by 2020, weather variability trends tend to remain scarce for the region (Cruz et al., 2007).

The Gangetic plain is spread across an area of 2, 40, 928 km² in state of Uttar Pradesh (UP) in India and constitutes about 85% of its total geographical area. It contributes significantly (22%) to India's granary besides supporting food, nutrition and livelihood security of 199.58 million populace. Being bracketed between Himalayan foothills in north, central plateau and hills in south, it is strongly connected to Himalayan tectonics and climate (Abrol et al., 2000; Aggarwal et al., 2006; Milesi et al., 2010; Pathak et al., 2003). It owns an extensive tract of uninterrupted alluvium made from deep, river-deposited sediments which turn the soils fertile (UPSAPCC, 2014). The plain is characterized by wide temperature variations in different seasons ranging from mean temperature of about 2–3 °C in winter to about 45 °C in summer season, with an average annual rainfall of 900–1200 mm. It depends on water from the perennial rivers systems of Ganga, Yamuna, Ghaghara, Gomati and Sharda, their tributaries and rainfall (Attri & Tyagi, 2010). The well-marked period for annual rains and variations in thermal regime through the year delineates IGP into three distinct crop growing seasons, *kharif* (June–October), *rabi* (October–March) and *zayad* (March–May). About 65% of the population comprising of farmers and agricultural labourers are directly dependent on agriculture (Roy & Ahmad, 2015). Prevalence of sub-tropical climate with hot humid summers, monsoon rains and cold dry winters is conducive for cultivation of cereals, pulses, oilseeds, forages, vegetables and plantation crops with 150–175% cropping intensity per year (Roy & Ahmad, 2015; Singh et al., 2004). Though staple food crops, rice and wheat occupy two thirds of 16.41 million ha net sown area, sugarcane remains the prime crop among the commercial crops and covers about 2.30 million ha. It thus is the mainstay of rural economy, providing raw material to 119 sugar mills and produces 12 million tonnes of sugar annually (India State of Forest Report, 2017; Verma et al., 2019).

Sugarcane crop requires variable thermal and hydrological regimes during its four different growth phases, viz. germination (February–March), tillering (April–June), grand growth (June to mid-October) and maturity (November to February) in 12 months (Moore & Frederik, 2014; Shrivastava et al., 2016; Verma et al., 2019). IPCC (2013) has enlisted increase in temperature, frequent droughts, floods and increased rainfall with greater intensity for the region. The changes will affect the crop physiology as an increase in temperature from 35 °C disrupts the central enzyme Rubisco, ceases photosynthesis, damages Photosystem II (PS II), nitrogen metabolism and lipid peroxidation (Griffin et al., 2004; Xu & Zhou, 2006; Tebaldi et al., 2018; Bonan et al., 2018). IPCC (2013) also projected an early maturity of rice with lower yield due to advancing of critical temperature to October in north India and 51% loss in wheat yield due to heat stress at maturity.

Climate change induced seasonal weather aberrations like excess or scanty rainfall during monsoon, heat wave during summer months and severe cold during winters or abnormally warm winters not only adversely impact cereal, pulse and oilseed yield, but also govern the cane and sugar production (Srivastava et al., 2013). Proneness to drought, rainfall deficit in July and greater reliance on ground water resources render IGP to be highly sensitive to climate change (Rao et al., 2013). Using a panel data approach for assessment of inter-annual variability in temperature and precipitation in India, Guiteras (2007) reported a loss in crop yields ranging from 4.5 to 9% by 2035 if suitable adaptation measures are not implemented. Yaduvanshi and Ranade (2015) reported that by 2050, at least 50% of IGP will become heat-stressed due to glacier melting, heat waves and cause severe reduction in crop yields affecting about 200 million people adversely. Since income from sugarcane sustains the input supply for other crops in the system, any negative impact on sugarcane productivity jeopardizes the overall agrarian economy (Ramesh Chand et al., 2012; Srivastava et al., 2013). As IGP in UP is among the most fertile and productive agro-ecological regions of the World (Chattopadhyay et al., 2019), the present study was undertaken to determine the weather variability trends and analyse their effects on the prevailing cropping systems. The study was carried out with the null hypothesis that variation in annual, seasonal and monthly weather over the period did not follow any trend. The objectives of the study were (i) to analyse the long-term trends of variation for major weather parameters over Gangetic plains of UP (ii) to assess the impact of weather variability on component crops of sugarcane-based cropping systems and (iii) to propose suitable adaptation measures for assisting the growers, state government officials and policy makers for minimizing the probable adverse effects of climate change.

2 Methodology and data

2.1 Study area and data collection

The study was conducted in the Gangetic plains of UP, India (Fig. 1). It is located between 23° 52' N to 31° 28' N latitude and 77° 51' E to 84° 38' E longitude that stretches over 20.7 million hectares which is more than 85% of the total geographical area of 24.09 million hectares. It has a table-top appearance with an average altitude of 168 m and rises in elevation from east to west and south to north with an average increase in 2 m km⁻¹ of distance. It is made from loamy alluvium soil brought by river Ganges and its tributaries, with available water capacity ranging from 50 to 250 mm m⁻¹. The soils belong to orders inceptisol (70%) and entisol (18.8). About 85% of soils are classified under arable classes I to IV of

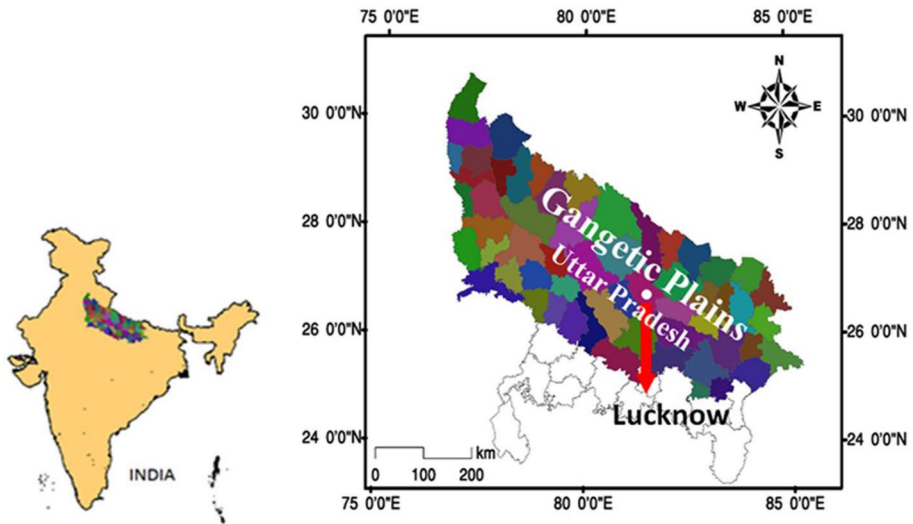


Fig. 1 Location of the meteorological station used for this study and map of the Gangetic plains of Uttar Pradesh

land capability classes of USDA classification (Singh et al., 2004). The sub-tropical climate is characterized by cold winters, hot humid summers and monsoon rains. The annual average precipitation is about 946 mm. The major cereal and leguminous crops grown are rice, wheat, maize, sorghum, pearl millet, barley, chick pea, peas, lentil, green gram, black gram, pigeon pea and beans. Along with rapeseed, mustard, sesame, soybean, sunflower and groundnut are grown in different crop rotations, while sal, teak, rosewood, poplar and eucalyptus are the timber trees that dot the plains.

UP is divided into 75 revenue districts of which 65 districts were considered for the study (Attri & Tyagi, 2010). The long-term trend of climatic variables across 65 districts truly represents the climate change in the IGP of UP. The study was undertaken at Agrometeorological Observatory, ICAR-Indian Institute of Sugarcane Research, Lucknow, UP, India, located at $26^{\circ} 80' N$, $80^{\circ} 94' E$, 111 m above mean sea level, characterized with semi-arid sub-tropics with cold winter and dry hot summer. The site being centrally located effectively represents the weather and agro-ecological conditions of UP. The daily meteorological datasets of weather variables viz. temperature (minimum and maximum), rainfall, rainy days, evaporation, wind speed, relative humidity (morning hours at 7:30 h and afternoon hours at 2:30 h) and bright sunshine (BSS) hours recorded during 1956–2018 at the observatory were examined carefully and systematically compiled on monthly basis.

2.2 Temporal trend analysis

Daily data of weather variables viz., temperature (minimum and maximum), rainfall, rainy days, evaporation, wind speed, relative humidity (morning and afternoon) and bright sunshine hours were used for monthly, annual and long-term trend analysis for the period 1956–2018 by using most suitable non-parametric Man-Kendall method (Djaman et al., 2016; Kendall, 1975; Mann, 1945). The method widely accepted for its efficiency to detect monotonic deviations in climatic and hydrological trends has

advantages of a non-parametric test and with this normal distribution of data is not required and it sans sensitivity to the abrupt breaks in homogeneous time series. The null hypothesis (H_0) under this test holds that data are not correlated and randomly ordered meaning thereby no trend in the data, against the alternative hypothesis (H_1) that there is a trend in the data. The Mann–Kendall test statistic S is computed as follows:

$$S = \sum_{j=1}^{n-1} \sum_{i=j+1}^n \text{sign}(x_i - x_j)$$

where x_i is the data value at time i , n is the length of the data set and $\text{sign}(x_i - x_j)$ is the sign function which can be computed as

$$\text{Sign}(x_i - x_j) = \begin{cases} 1 & \text{If } (x_i - x_j) > 0 \\ 0 & \text{If } (x_i - x_j) = 0 \\ -1 & \text{If } (x_i - x_j) < 0 \end{cases}$$

For $n > 10$, the test statistic Z approximately follows a standard normal distribution

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & \text{If } S > 0 \\ 0 & \text{If } S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & \text{If } S < 0 \end{cases}$$

in which, $\text{Var}(S)$ is the variant of statistic S .

The value of Z shows the type of trend in data series. The increasing trend in data series is indicated by the positive values of Z , whereas declining trend is indicated by the negative values of Z . The null hypothesis that there is no trend in the data series can either be accepted or rejected depending on the critical value of Z obtained from normal distribution table at 5% significance level (Some'e, 2013). If the computed value of Z is found greater than the table value, then the null hypothesis was rejected and alternate hypothesis that there is a trend in data series was accepted.

The magnitude of linear/monotonic trend with time was computed with Theil-Sen estimator (TSE) that computes both the slope (linear rate of change) and the intercepts according to Sen's method (Sen, 1968). The TSE is robust with a high breakdown point of 29.3%, has a bounded influence function and possesses a high asymptotic efficiency. In the event of a trend in the data, the extent of the change in any variable can be denoted by trend slope β (Sen, 1968; Theil, 1950).

$$\beta = \text{median} \left(\frac{x_i - x_j}{i - j} \right) \forall j < i$$

where x_i and x_j are the values at times t_i and t_j ($i > j$), respectively.

A linear regression analysis was done to detect and analyse the trends in time series data of weather parameters. The slope drawn from the regression analysis was the main statistical parameter that highlights the change in climatic variables during 63 years. The statistical analysis Man–Kendall test was done by using the XL Stat software version. 2018 and the figures were drawn using software ArcGIS 10 and Origin 2020.

3 Results and discussion

3.1 Trend in climate change

3.1.1 Annual, seasonal and monthly mean maximum and minimum temperature trends

Based on a long duration of 63 years (1956–2018), significant trends and marked degree of variation both in mean maximum (T_{\max}) and minimum (T_{\min}) temperatures were recorded over Gangetic plains of UP (Fig. 2). Significant ($p < 0.05$) increasing trend in mean annual T_{\min} amounting to $0.09\text{ }^{\circ}\text{C}$ decadal rise was observed (Table 1; Fig. 2a). The annual T_{\min} ranged between 15.57 and $19.75\text{ }^{\circ}\text{C}$ with a mean of $18.10\text{ }^{\circ}\text{C}$. Skewness (-1.14) and kurtosis (3.06) tendencies showed wide variation in minimum temperature. Increase in mean T_{\min} was significant ($p < 0.05$) for summer (March to June) and winter (October to February) seasons (Fig. 3). T_{\min} varied within a range of 16.90 – $21.91\text{ }^{\circ}\text{C}$ with a mean of $19.92\text{ }^{\circ}\text{C}$ in summers, whereas for the winter months, it ranged from 8.78 to $13.28\text{ }^{\circ}\text{C}$ with mean $11.11\text{ }^{\circ}\text{C}$. There was no significant change in average T_{\min} for monsoon season (June to October); however, summer and winter seasons witnessed a decadal increasing rate of $0.12\text{ }^{\circ}\text{C}$ (Table 1). Indian Meteorological Department has also reported about increasing trend in minimum temperature over various parts of India including Gangetic plains of UP

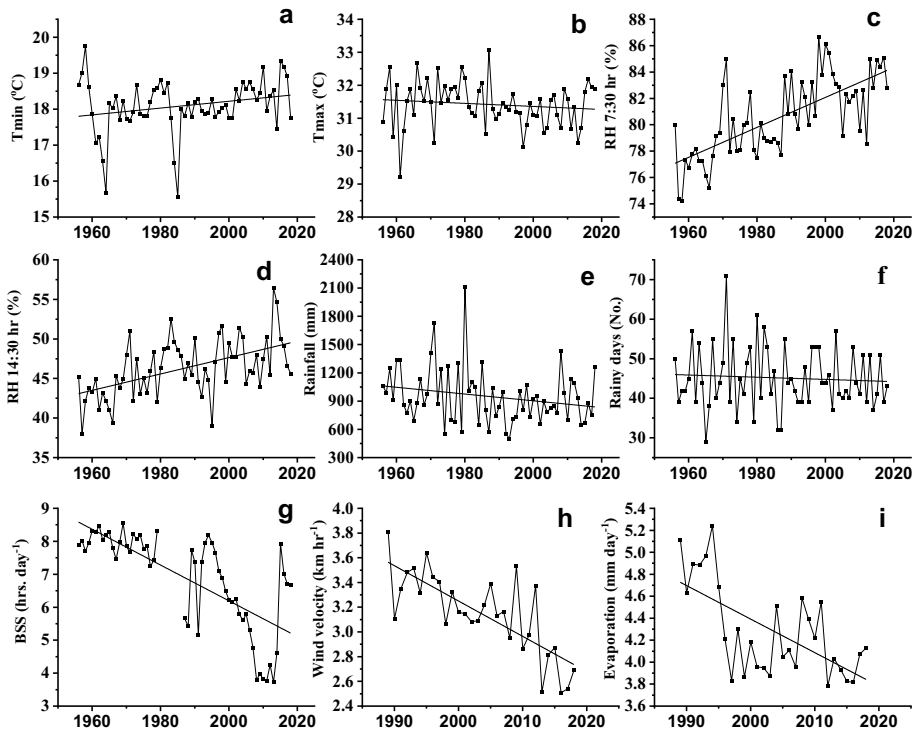


Fig. 2 Annual weather variability trends for T_{\min} (a), T_{\max} (b), RH 730 hr (c), RH 1430 h (d), rainfall (e), rainy days (f), BSS (g), wind velocity (h), and evaporation (i) during 1956 to 2018

Table 1 Descriptive statistics and long-term trend of seasonal and annual weather parameters in Gangetic Plain of Uttar Pradesh during 1956 to 2018

Variables	Seasons	Summer/Kharif	Monsoon	Winter or Rabi	Annual
Minimum temperature (°C)	No. of years	63	63	63	63
	Minimum	16.90	21.98	8.78	15.57
	Maximum	21.91	28.04	13.28	19.75
	Mean	19.92	25.46	11.11	18.10
	SD	0.88	0.95	0.85	0.74
	Skewness	-0.22	-1.24	-0.36	-1.14
	Kurtosis	1.78	3.71	1.16	3.06
	Sen's slope	0.01	0.01	0.01	0.01
	Significance	*	NS	**	*
	Decadal change	0.12	-	0.12	0.09
Maximum temperature (°C)	No. of years	63	63	63	63
	Minimum	30.00	30.34	24.04	29.22
	Maximum	38.44	37.35	27.92	33.08
	Mean	35.97	34.29	26.39	31.42
	SD	1.37	0.97	0.98	0.69
	Skewness	-1.39	-0.56	-0.77	-0.34
	Kurtosis	4.86	4.76	-0.01	0.73
	Sen's slope	-0.01	0.00	-0.01	-0.01
	Significance	NS	NS	*	NS
	Decadal change	-	-	-0.14	-
Relative humidity (%) 7:30 h	No. of years	63	63	63	63
	Minimum	46.27	75.33	84.08	74.20
	Maximum	76.53	90.40	95.30	86.67
	Mean	60.69	84.09	89.78	80.60
	SD	6.06	3.33	2.85	3.00
	Skewness	0.17	-0.31	0.03	0.03
	Kurtosis	0.07	-0.27	-0.73	-0.77
	Sen's slope	0.19	0.08	0.10	0.12
	Significance	**	**	**	**
	Decadal change	1.86	0.77	1.02	1.18
Relative humidity (%) 14:30 h	No. of years	63	63	63	63
	Minimum	14.43	52.13	35.26	38.00
	Maximum	44.47	72.35	59.48	56.47
	Mean	26.52	64.13	44.11	46.30
	SD	5.83	4.47	4.95	3.65
	Skewness	0.56	-0.55	0.79	0.22
	Kurtosis	0.95	0.25	0.83	0.27
	Sen's slope	0.13	0.04	0.13	0.10
	Significance	**	NS	**	**
	Decadal change	1.31	-	1.32	0.99

SD standard deviation

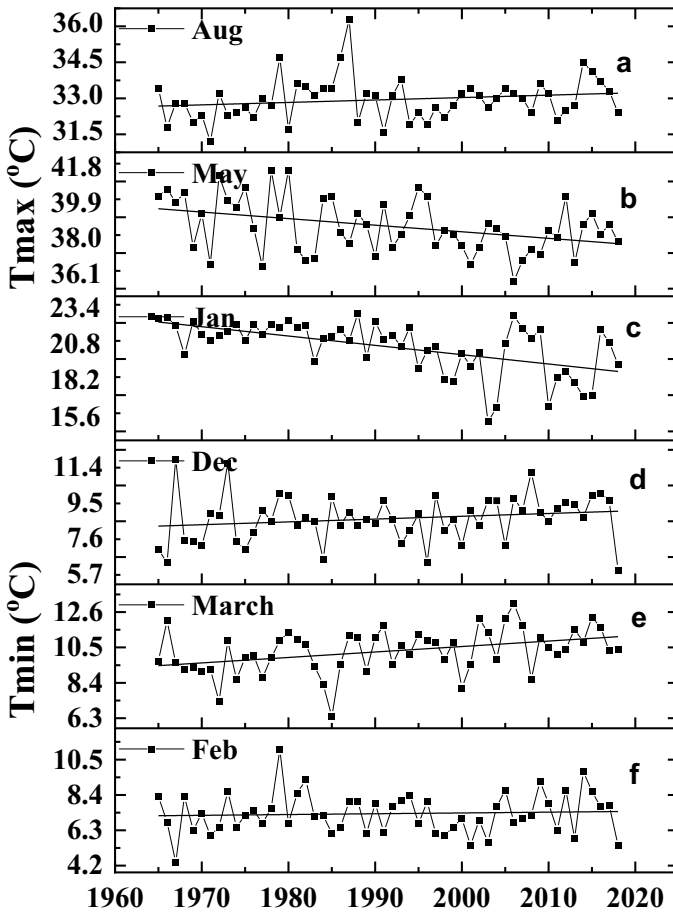


Fig. 3 Monthly trends for T_{\max} for significant months of Aug (a), May (b), Jan (c) and T_{\min} (b) for significant months of Dec (d), March (e) and Feb (f) during 1956 to 2018

(Rathore et al., 2013). There was no significant increasing or declining trend in average annual T_{\max} and it varied between 29.22 and 33.08 °C with mean of 31.42 °C (Table 1; Fig. 2b). Seasonal average T_{\max} for summer and monsoon seasons did not exhibit any significant trend, while winter season experienced significant ($p < 0.05$) decline of -0.14 °C per decade (Table 1; Fig. 4b). Considering the trends in average monthly T_{\max} and T_{\min} for the same period, the analyses revealed that T_{\min} recorded significant ($p < 0.05$) increase for the months February, March and December with per decade increasing rate of 0.33, 0.29 and 0.17 °C, respectively (Table 2; Fig. 5d–f). While mean monthly T_{\max} showed significantly declining ($p < 0.05$) trend for the months of January and May with respective decadal rate of decline being -0.41 , -0.28 °C, T_{\max} for August was found significantly ($p < 0.05$) rising with decadal change rate of 0.14 °C (Table 2; Fig. 5a–c).

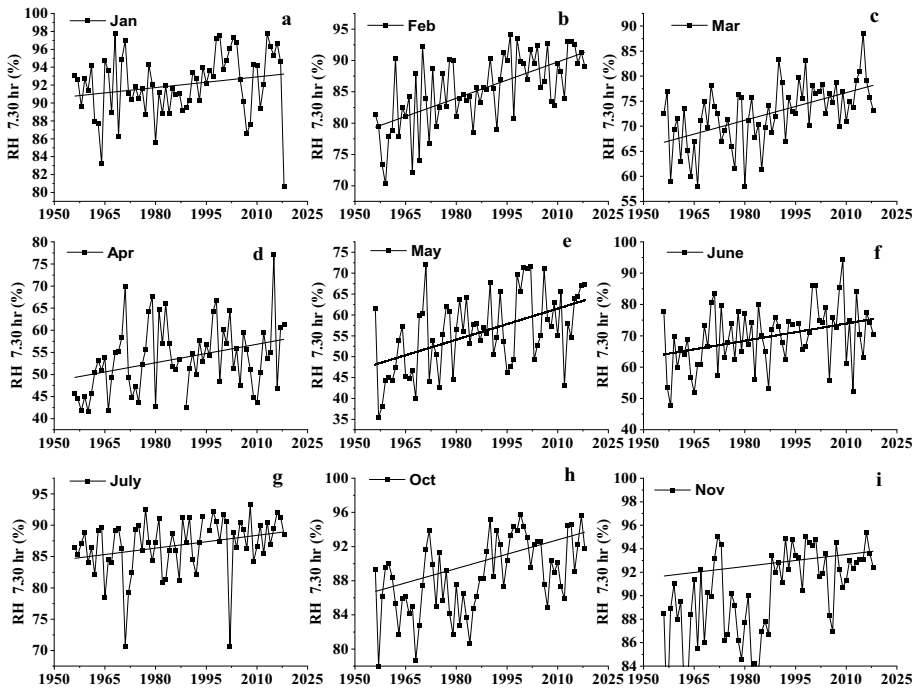


Fig. 4 Monthly trends for RH 730 h for significant months during 1956 to 2018

Significant rise in mean annual and seasonal T_{\min} for summer and winter seasons has been reported for Upper Gangetic plains of India (Verma et al., 2019). Conspicuous enhancement in the mean monthly T_{\min} of February, March and December (Fig. 5d–f) may potentially interfere with various growth phases of cereals, pulses, oilseeds and vegetable crops grown during summer and winter seasons. Kumar et al. (2011) reported that grain filling and maturity stages in wheat suffer with poor grain filling and shrivelled grains in February–March. Whereas, significant decline ($p < 0.01$) in T_{\max} in January by -0.41 °C per decade might hamper tillering timing and duration. Tillering in sugarcane might also get affected owing to significant reduction in mean monthly T_{\min} of May by -0.28 °C per decade as hot and dry climate is conducive for profuse tillering (Moore and Frederick, 2014). As tillering forms the base for harvestable number of millable canes contributing about 70% to cane yield, its reduction has potential to decrease cane yield. Soil quality enhancement through conservation tillage, organic amendments, precision nutrient management and trench planting thus needs to be adopted for its improvement.

3.1.2 Annual, seasonal and monthly mean relative humidity (RH) trends

Significant increasing ($p < 0.01$) trend was observed in morning and afternoon RH over the period for mean annual (Table 1; Fig. 2c, d) and seasonal RH except for afternoon RH during monsoon season (Table 1). The morning mean annual RH over the period ranged within 74.20 to 86.67% with average being 80.60%, while afternoon RH varied from 38.00 to 56.47% with mean 46.30%. Morning RH during summers varied between 46.27 and

Table 2 Descriptive statistics and long-term trend of seasonal and annual rainfall, rainy days, wind speed and bright sunshine hours in Gangetic Plain of Uttar Pradesh during 1956 to 2018

Variables	Seasons	Summer or Kharif	Monsoon	Winter or Rabi	Annual
Rainfall (mm) 1956–2018	No. of years	63	63	63	63
	Minimum	0.00	437.50	4.00	502.40
	Maximum	117.90	2037.10	290.90	2113.90
	Mean	34.54	829.00	86.17	949.71
	SD	29.03	279.55	70.65	295.42
	Skewness	0.91	1.59	1.39	1.33
	Kurtosis	0.41	4.65	1.71	3.00
	Sen's slope	0.02	-3.18	-0.35	-2.90
	Significance	NS	*	NS	*
	Decadal change	-	-31.76	-	-28.97
	Rainy days (Nos.) 1956–2018	No. of years	63	63	63
Minimum		0.00	21.00	1.00	29.00
Maximum		12.00	52.00	14.00	71.00
Mean		3.14	36.63	5.35	45.13
SD		2.59	6.75	2.94	7.89
Skewness		1.09	-0.17	0.72	0.62
Kurtosis		1.07	0.20	0.35	0.64
Sen's slope		0.00	-0.04	0.00	0.00
Significance		NS	NS	NS	NS
Decadal change		-	-	-	-
Evaporation (mm day ⁻¹) 1989–2018		No. of years	29	29	29
	Minimum	5.77	3.53	1.72	3.78
	Maximum	9.77	5.30	3.08	5.24
	Mean	7.38	4.42	2.33	4.29
	SD	1.04	0.48	0.38	0.43
	Skewness	0.74	-0.19	0.51	0.73
	Kurtosis	0.38	-0.89	-0.60	-0.60
	Sen's slope	-0.06	-0.01	-0.03	-0.03
	Significance	**	NS	**	**
	Decadal change	-0.56	-0.14	-0.30	-0.31
	Wind speed (km h ⁻¹)	No. of years	30	30	30
Minimum		3.60	2.18	1.58	2.51
Maximum		6.20	4.40	2.92	3.81
Mean		4.57	3.24	2.23	3.15
SD		0.63	0.49	0.33	0.33
Skewness		0.91	0.01	-0.06	-0.31
Kurtosis		0.57	0.03	-0.45	-0.31
Sen's slope		-0.05	-0.03	-0.02	-0.03
Significance		**	**	*	**
Decadal change		-0.46	-0.34	-0.20	-0.29

Table 2 (continued)

Variables	Seasons	Summer or Kharif	Monsoon	Winter or Rabi	Annual
Bright sunshine (h day ⁻¹) 1956–2018	No. of years	36	36	36	36
	Minimum	6.27	4.48	3.66	5.16
	Maximum	10.13	8.90	9.00	8.55
	Mean	9.01	6.37	7.86	7.67
	SD	0.70	0.81	1.11	0.79
	Skewness	-1.88	0.15	-2.35	-2.01
	Kurtosis	5.71	2.37	6.24	4.03
	Sen's slope	-0.01	-0.02	-0.03	-0.02
	Significance	NS	*	**	**
	Decadal change	-	-0.17	-0.29	-0.19

SD standard deviation

76.53%. Decadal rate of increase for the season was estimated to be 1.86% against afternoon RH variability from 14.43 to 44.47 and per decade increase of 1.31%. This explains the increasing incidence of leaf curl virus spread through aphids and flies thriving under humid conditions (Srinivasan et al., 2012). Pulses and oilseeds are potentially at risk as unusual increase in RH at crucial stages of flowering and anthesis affects pollen viability and seed setting (Sita et al., 2017). Monsoon season morning RH ranged within 75.33 and 90.40 with a mean of 84.09% and rate of per decade increase was 0.77%.

Winters showed significantly increasing ($p < 0.01$) trend in morning and afternoon RH (Fig. 4c, d). While morning RH varied between 84.08 and 95.30 with average 89.78%, it was 35.26 to 59.48 with a mean 46.30% in the afternoon. Winter season morning RH

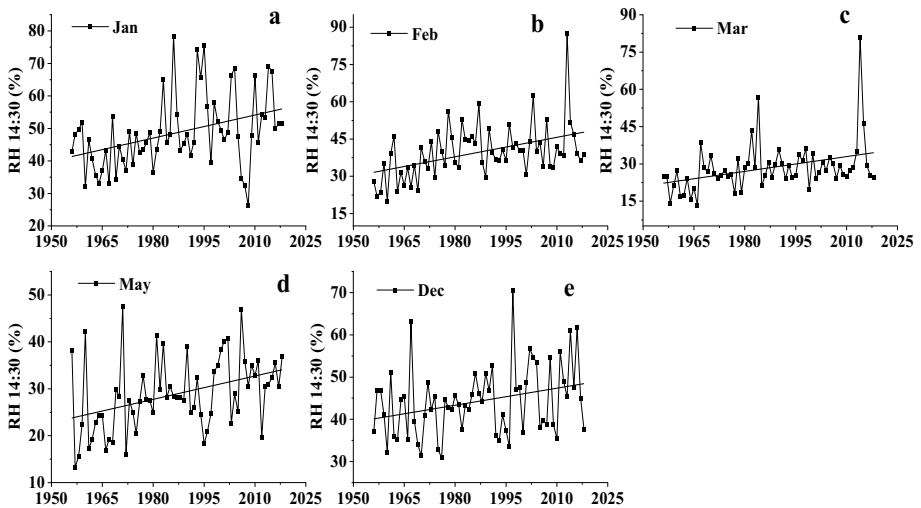


Fig. 5 Monthly trends for RH 1430 h for significant months during 1956 to 2018

Fig. 6 Monthly trends for rainfall (a) and number of rainy days (b) for significant month August during 1956 to 2018

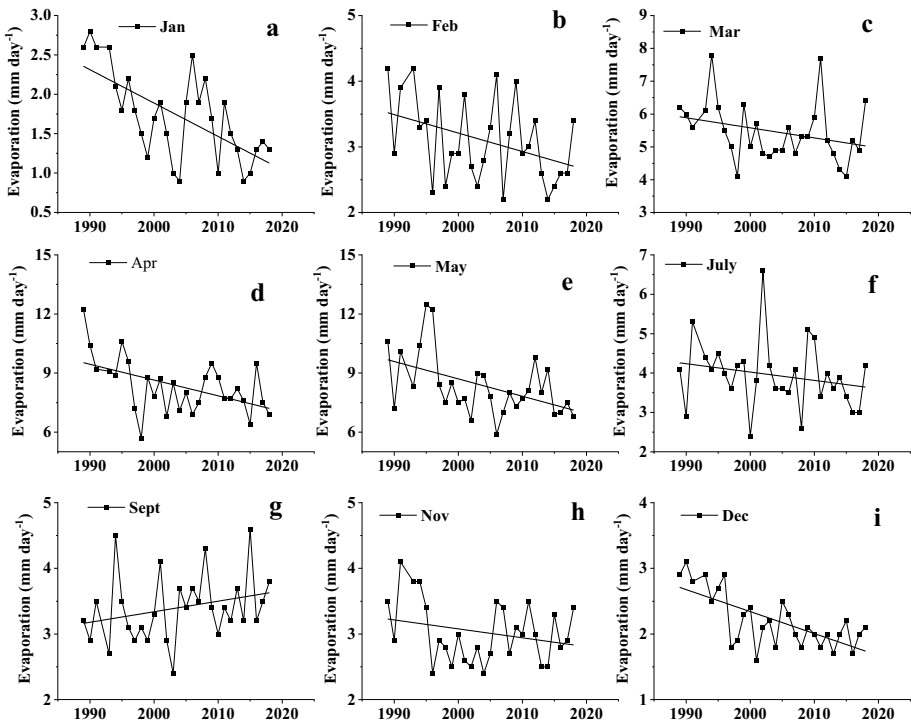
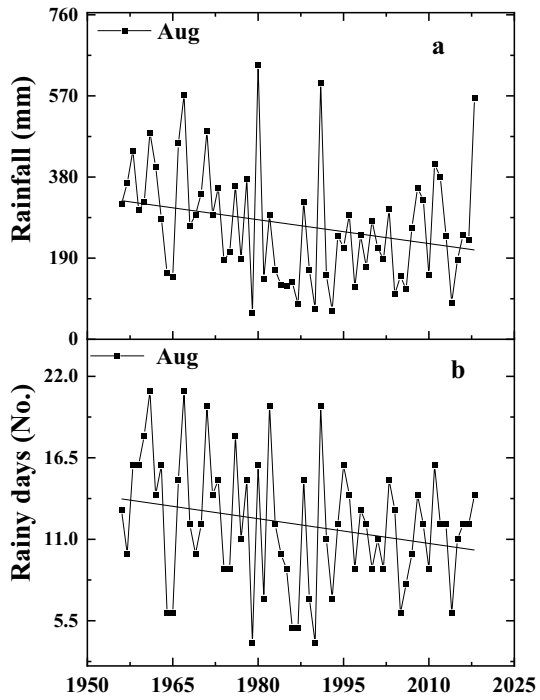


Fig. 7 Monthly trends for evaporation for significant months during 1990-2018

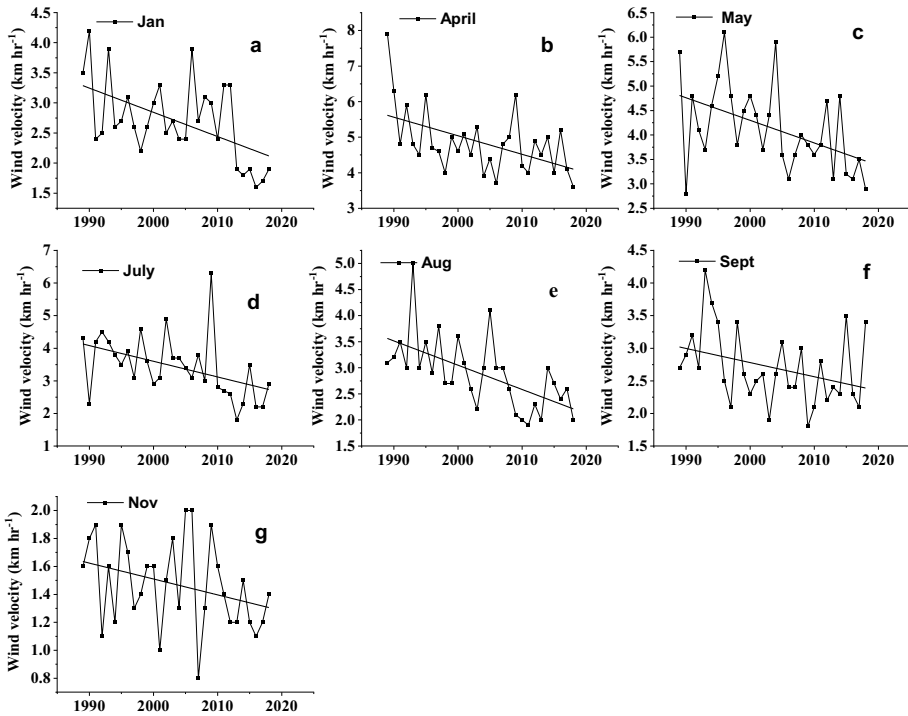


Fig. 8 Monthly trends for wind velocity for significant months during 1990-2018

increased at the decadal change rate of 1.02 against 1.32% in the afternoon (Table 1). Except for August and September, monthly mean morning RH, showed significant increasing trend (Fig. 4) compared to increasing trend recorded for February, March, April, June and December for the afternoon RH (Fig. 5). Overall, mean morning RH declined from January to April (92.00 to 53.64%) and thereafter increased till December (55.52 to 92.73%). Contrary to this, afternoon mean RH though declined from January to April (48.68 to 22.24%), followed by an increasing trend from May to August, declining trend from September to November and again increased in December. The per decade rise in mean monthly morning RH was highest in May (2.75%), followed by February (1.96%), June (1.90%) and March (1.67%), whereas the rate of decadal rise in afternoon mean monthly RH was highest for January (2.25%) followed by February (2.24%), May (2.02%) and March (1.37%). Conspicuously, RH during monsoon months remained by and large unaffected (Figs. 4, 5). Afternoon RH 45 days prior to sugarcane harvest has been found to be negatively correlated with sugar content in juice (Moore & Frederick, 2014). As evident by 1.31% decadal increase in RH and sugar content being genetically controlled trait, it is imperative to develop varieties with high sugar content in the region.

3.1.3 Trend in annual, seasonal and monthly rainfall and number of rainy days

During the period of last 63 years (1956–2018), significant ($p < 0.05$) decline in rainfall (Fig. 2 e) was observed, and a reduction of 28.97 mm in annual rainfall per decade has been marked (Table 3). The average annual rainfall was 949.71 mm that varied in

Table 3 Descriptive statistics and long-term trend of monthly weather variables in Gangetic Plain of Uttar Pradesh during 1956 to 2018

Variables	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum temperature (°C)												
No. of years	63	63	63	63	63	63	63	63	63	63	63	63
Minimum	3.50	6.40	12.50	18.20	20.00	15.28	17.50	22.10	20.00	14.80	7.80	4.60
Maximum	11.10	13.10	17.89	24.70	27.70	29.39	34.17	26.89	25.78	21.94	16.80	10.90
Mean	7.29	10.13	14.75	20.48	24.54	26.38	25.90	25.50	24.06	18.55	11.87	7.71
SD	1.41	1.34	1.24	1.23	1.25	1.83	1.82	0.73	1.19	1.46	1.80	1.35
Skewness	-0.07	-0.37	0.37	0.94	-0.69	-3.63	-0.11	-2.05	-1.67	-0.59	0.23	-0.14
Kurtosis	0.39	0.11	-0.21	1.30	2.05	21.65	13.25	7.14	2.96	0.51	0.99	0.20
Sen's slope	0.00	0.03	0.03	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02
Significance	NS	**	**	NS	NS	NS	NS	NS	NS	NS	NS	*
Decadal change												
No. of years	-	0.33	0.29	-	-	-	-	-	-	-	-	0.17
Maximum temperature (°C)												
No. of years	63	63	63	63	63	63	63	63	63	63	63	63
Minimum	16.30	20.69	25.20	18.10	36.50	24.44	31.00	31.20	30.50	20.20	20.50	18.90
Maximum	24.33	29.70	35.20	41.10	42.61	42.40	37.60	36.30	37.30	41.40	31.40	25.90
Mean	21.76	25.51	31.39	37.06	39.47	37.83	33.61	32.86	32.86	32.31	28.52	23.84
SD	1.79	1.80	1.72	3.20	1.50	2.68	1.21	0.88	1.12	2.26	1.42	1.27
Skewness	-1.17	-0.03	-0.48	-3.87	0.26	-1.99	0.83	1.07	1.21	-1.51	-2.94	-1.90
Kurtosis	0.97	0.33	1.83	20.66	-0.87	8.99	1.60	2.79	3.57	16.25	16.23	4.68
Sen's slope	-0.04	-0.01	0.00	-0.01	-0.03	-0.02	0.00	0.01	0.01	0.00	0.00	-0.01
Significance	**	NS	NS	NS	**	NS	NS	**	NS	NS	NS	NS
Decadal change												
No. of years	-0.41	-	-	-	-0.28	-	-	0.14	-	-	-	-

Table 3 (continued)

Variables	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Relative humidity (%)												
7:30 h												
No. of years	63	63	63	62	63	62	62	62	63	63	63	63
Minimum	80.70	70.30	57.90	41.70	35.50	47.70	70.60	70.80	77.70	78.00	79.50	85.10
Maximum	97.80	94.20	88.60	77.10	72.20	94.30	93.30	97.10	95.40	95.80	95.40	98.10
Mean	92.00	85.33	72.49	53.64	55.82	69.68	86.81	89.88	89.61	88.63	90.21	92.73
SD	3.56	5.71	6.28	7.77	9.23	9.71	4.54	3.78	3.40	4.30	3.78	3.20
Skewness	-0.62	-0.58	-0.38	0.59	-0.07	-0.06	-1.57	-2.26	-1.13	-0.34	-0.75	-0.40
Kurtosis	0.72	-0.21	0.38	0.21	-0.76	-0.20	3.58	9.69	1.82	-0.45	-0.11	-0.56
Sen's slope	0.06	0.20	0.17	0.14	0.27	0.19	0.07	0.01	0.04	0.12	0.10	0.04
Significance	*	**	**	**	**	**	**	NS	NS	**	**	NS
Decadal change												
No. of years	0.58	1.96	1.67	1.39	2.75	1.90	0.67			1.15	1.00	0.58
Minimum	63	63	63	62	63	62	62	62	63	63	63	63
Maximum	26.30	20.00	13.30	11.90	13.30	14.10	49.80	58.60	42.30	32.10	25.00	26.30
Mean	78.40	87.60	80.90	43.40	47.60	69.40	81.10	84.60	81.70	70.40	55.50	78.40
SD	48.68	39.65	28.34	22.24	28.89	45.50	70.91	73.21	66.68	48.90	39.07	48.68
Skewness	11.40	10.81	9.89	7.25	7.84	10.88	5.98	5.51	7.01	8.95	6.30	11.40
Kurtosis	0.72	1.43	2.83	1.01	0.25	-0.12	-1.03	-0.63	-0.84	0.19	0.09	0.78
Sen's slope	0.30	5.25	12.91	0.88	-0.34	0.54	1.48	0.54	1.81	-0.45	0.10	0.71
Significance	0.23	0.22	0.14	0.07	0.20	0.09	0.05	-0.02	0.03	-0.06	0.10	0.13
Decadal change	**	**	**	NS	**	NS	NS	NS	NS	NS	NS	*
SD standard deviation	2.25	2.24	1.37	-	2.02	-	-	-	-	-	-	1.32

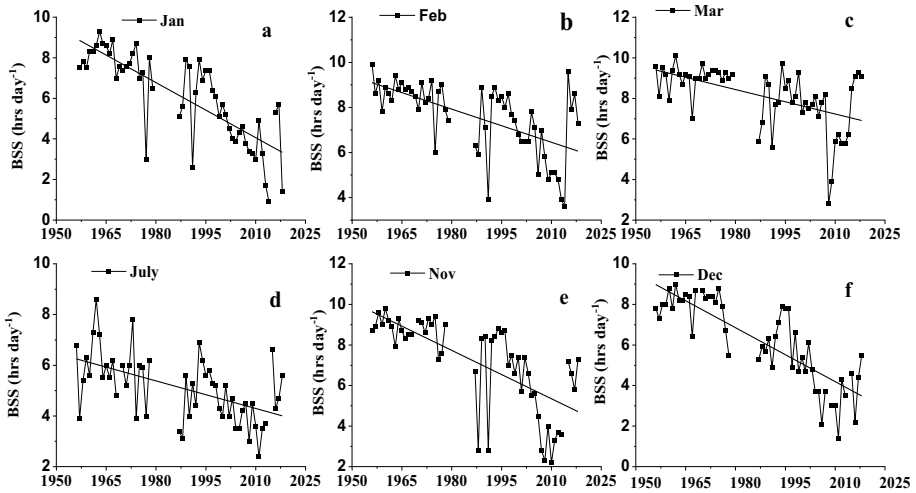


Fig. 9 Monthly trends for bright sunshine hours (BSS) for significant months during 1956 to 2018

the range 502.40–2113.90 mm for the period. While summer and winter season rains did not exhibit any trend, the monsoon rains (June–September) ranging from 437.50 to 2037.10 mm with mean 829 mm declined (Fig. 13b) significantly ($p < 0.05$) with per decade reduction rate of 31.76 mm (Table 3). Precipitation during monsoon season contributes 87.28% of the total annual rainfall, thus its decline may jeopardize cultivation of rice with its sizeable acreage (~45%) in the Gangetic plains (Dwivedi, 2013). Further, August, the wettest month, that receives 28.11% of total annual rainfall, suffered a significant ($p < 0.05$) decline (Fig. 6) in rains by 19.3 mm decline per decade. This again does not auger well for rice cultivation as more than 50% of rice transplanting is done during monsoonal rains. Total rainfall for the month during the period varied between 62.0 and 642.8 mm with mean 267.0 mm. Kumar et al. (2011) reported that conspicuous reduction by 1.5–1.9% in August rains was the major cause for annual loss of rice yield. For sugarcane, declining monsoon rains would hamper cane elongation and overall dry matter accumulation during its grand growth phase as it coincides with monsoonal months. Cane varieties with high moisture efficiency, drought tolerance and less water requiring crops viz., sorghum, pearl millet, finger millet etc., need to be adopted widely to arrest such deficit in productivity and production.

The Gangetic plains did not record significant trend in the temporal distribution of rainfall for the past 63 years as total number of rainy days annually or for a specific season remained trendless (Fig. 2f). This is contrary to the climate change induced aberrations in temporal distribution of rainfall being experienced in many other regions of the world. The plains on an average, receive rains for 45.13 days in a year, varying annually within the range 29 to 71 days (Table 3). The average number of rainy days was highest during monsoon (36.63) followed by winter (5.35) and summer (3.14) seasons. Mean monthly number of rainy days varied between 0.3 for November to 12.03 for July and 12.0 for August. No significant trend in the number of rainy days for different months was found except for August that showed significant reduction with decadal change rate of -0.48 days (Table 4). Dwivedi (2013) reported that August is the most crucial monsoon season month for agriculture and is critical for good start of farming calendar in Gangetic plains. But the trends

Table 4 Descriptive statistics and long-term trend of monthly rainfall, rainy days, wind speed and bright sunshine hours in Gangetic Plain of Uttar Pradesh during 1956 to 2018

Variables	Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec		
Rainfall (mm) 1956–2018	No. of years	63	63	63	63	63	63	63	63	63	63	63	63		
	Minimum	0.0	0.0	0.0	0.0	0.0	1.8	66.8	62.0	62.0	8.2	0.0	0.0	0.00	
	Maximum	98.4	144.3	57.1	54.0	89.3	426.4	741.7	642.8	698.5	698.5	265.7	50.5	98.3	
	Mean	16.2	15.0	8.0	5.3	21.3	110.3	265.8	267.0	186.0	186.0	42.2	4.2	8.5	
	SD	19.2	23.2	12.7	9.2	23.1	90.6	127.4	138.4	127.8	127.8	64.4	10.7	17.1	
	Skewness	2.06	3.34	2.24	3.00	1.29	1.31	1.30	0.76	1.72	1.72	2.15	3.48	3.40	
	Kurtosis	5.20	15.19	4.96	12.33	1.10	1.94	2.52	0.18	4.94	4.94	4.48	11.82	13.83	
	Sen's slope	0.00	0.08	0.00	0.00	0.06	0.35	-0.30	-1.93	-0.60	-0.60	0.00	0.00	0.00	
	Significance	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	
	Decadal change	-	-	-	-	-	-	-	-	-19.3	-	-	-	-	
	Rainy days (Nos.) 1956–2018	No. of years	63	63	63	63	63	63	63	63	63	63	63	63	
		Minimum	0.00	0.00	0.00	0.00	0.00	0.00	5.00	4.00	4.00	1.00	0.00	0.00	0.00
		Maximum	4.00	6.00	6.00	3.00	9.00	12.00	20.00	21.00	17.00	17.00	9.00	2.00	4.00
		Mean	1.29	1.40	0.86	0.56	1.73	4.71	12.03	12.00	7.89	7.89	1.68	0.30	0.68
SD		1.10	1.61	1.28	0.82	1.74	2.59	3.30	4.28	3.30	3.30	2.00	0.56	1.01	
Skewness		0.53	1.30	1.89	1.36	1.51	0.30	0.22	0.16	0.31	0.31	1.51	1.71	1.45	
Kurtosis		-0.44	0.99	3.89	1.05	3.62	0.07	-0.42	-0.44	0.01	0.01	2.34	2.08	1.33	
Sen's slope		0.00	0.00	0.00	0.00	0.00	0.02	0.00	-0.05	0.00	0.00	0.00	0.00	0.00	
Significance		NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	
Decadal change		-	-	-	-	-	-	-	-0.48	-	-	-	-	-	

Table 4 (continued)

Variables	Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Evaporation (mm day ⁻¹) 1989–2018	No. of years	29	29	29	29	29	29	29	29	29	29	29	29	
	Minimum	0.90	2.20	4.10	5.70	5.90	4.00	2.40	2.40	2.40	2.40	2.40	1.60	0.80
	Maximum	2.80	4.20	7.80	12.20	12.50	10.10	6.60	6.60	5.20	4.60	4.10	3.10	2.90
	Mean	1.72	3.10	5.46	8.33	8.36	6.82	3.94	3.94	3.51	3.40	3.02	2.21	1.61
	SD	0.56	0.63	0.90	1.39	1.59	1.48	0.85	0.90	0.70	0.51	0.46	0.42	0.47
	Skewness	0.29	0.35	0.96	0.64	1.13	-0.04	0.90	0.90	0.28	0.64	0.55	0.63	0.52
	Kurtosis	-0.87	-1.07	1.21	0.87	1.01	0.09	2.32	2.32	-0.32	0.45	-0.52	-0.65	0.59
	Sen's slope	-0.05	-0.03	-0.04	-0.08	-0.07	-0.01	-0.03	-0.03	-0.03	0.02	-0.01	-0.03	-0.03
	Significance	**	**	*	**	**	0.30	*	*	0.07	*	0.18	**	**
	Decadal change	-0.45	-0.25	-0.37	-0.76	-0.73	-	0.27	0.27	-	0.16	-	-0.33	-0.27
Wind speed (km h ⁻¹)	No. of years	30	30	30	30	30	30	30	30	30	30	30	30	
	Minimum	1.60	2.50	3.30	3.60	2.80	2.50	1.80	1.80	1.90	1.80	0.80	0.80	1.10
	Maximum	4.20	5.20	7.50	7.90	6.10	6.10	6.30	6.30	5.00	4.20	2.20	2.00	2.50
	Mean	2.70	3.61	4.73	4.86	4.14	3.92	3.43	3.43	2.89	2.70	1.58	1.47	1.77
	SD	0.67	0.73	0.87	0.91	0.88	0.86	0.96	0.96	0.69	0.57	0.30	0.32	0.36
	Skewness	0.35	0.31	1.18	1.53	0.56	0.52	0.74	0.74	1.00	0.85	-0.30	-0.01	0.03
	Kurtosis	-0.23	-0.86	2.34	3.25	-0.28	-0.05	1.30	1.30	1.97	0.46	0.47	-0.81	-0.73
	Sen's slope	-0.04	-0.03	-0.03	-0.04	-0.05	-0.01	-0.07	-0.07	-0.04	-0.02	0.00	-0.01	0.00
	Significance	**	NS	NS	**	**	NS	**	**	**	*	NS	*	NS
	Decadal change	-0.38	-	-	-0.38	0.54	-	-0.67	-0.67	-0.42	-0.21	-	-0.13	-

Table 4 (continued)

Variables	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bright sunshine (h day ⁻¹) 1956–2018												
Months	35	36	36	36	36	36	34	34	34	34	34	34
No. of years	2.60	3.90	5.60	6.50	6.40	4.90	3.10	2.80	3.50	3.60	2.80	4.90
Minimum	9.30	9.90	10.10	10.10	10.40	10.50	8.60	7.00	9.30	9.50	9.80	9.00
Maximum	7.28	8.22	8.67	9.07	9.29	7.28	5.61	5.50	6.76	8.18	8.24	7.43
Mean	1.46	1.16	1.04	0.83	0.82	1.14	1.22	1.15	1.33	1.37	1.55	1.21
SD	0.35	0.31	1.18	1.53	0.56	0.52	0.74	1.00	0.85	-0.30	-0.01	0.03
Skewness	-0.23	-0.86	2.34	3.25	-0.28	-0.05	1.30	1.97	0.46	0.47	-0.81	-0.73
Kurtosis	-0.04	-0.03	-0.02	-0.01	-0.01	0.00	-0.02	-0.01	-0.03	0.00	-0.03	-0.04
Sen's slope	**	**	**	NS	NS	NS	*	NS	NS	NS	**	**
Significance	-0.42	-0.25	-0.22	-	-	-	-0.24	-	-	-	-0.28	-0.40
Decadal change												

SD standard deviation

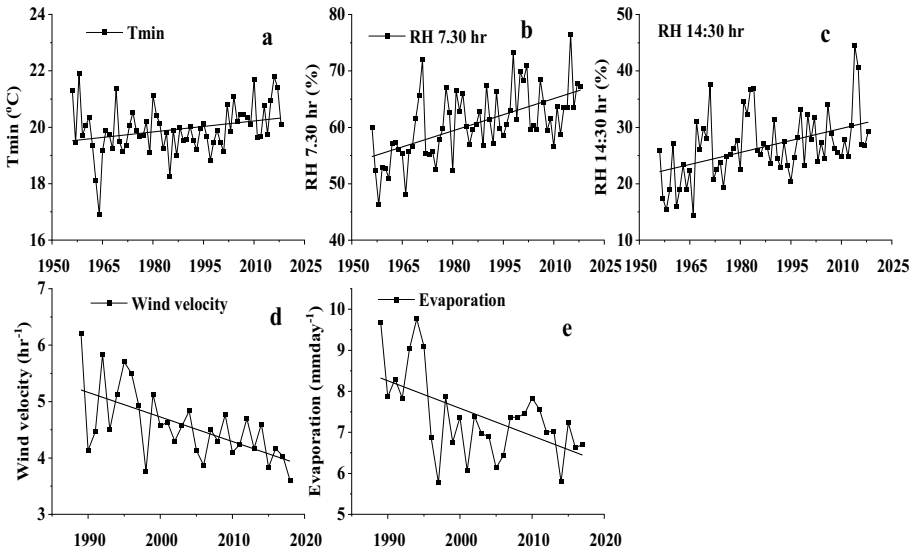


Fig. 10 Summer season trends for T_{min} (a), RH 730 h (b), RH 1430 h (c), wind velocity (d) and evaporation(e) during 1956 to 2018

indicate conspicuous reduction in precipitation for the season with sizeable inter-annual variability as exhibited by positive skewness in the data. Similar trends are being

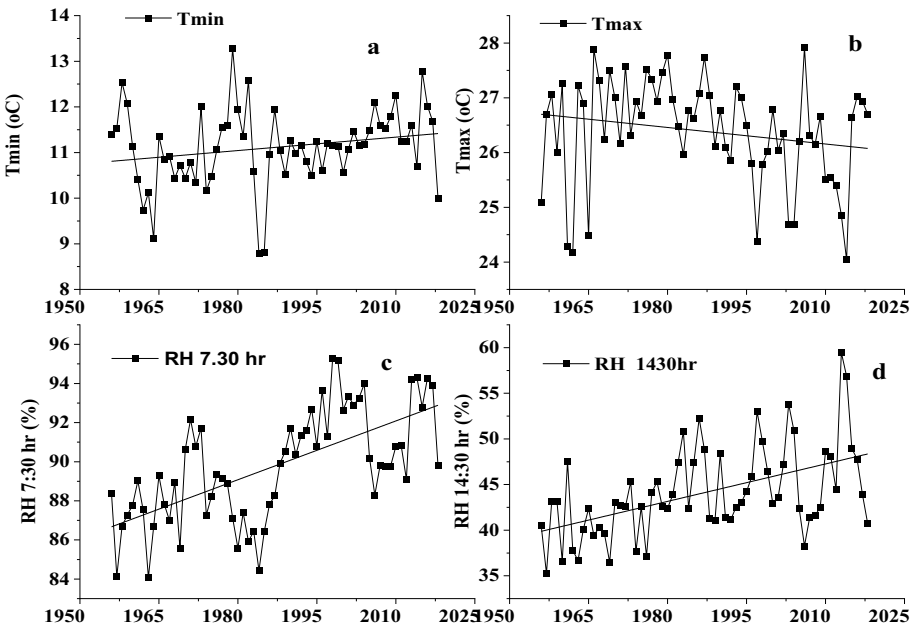


Fig. 11 Winter season trends for T_{min} (a), T_{max} (b) RH 730 h (c), RH 1430 h (d), during 1956 to 2018

increasingly analysed and reported from different agro-climatic regions of India and other tropical countries (IPCC, 2013).

3.1.4 Trends in mean annual, seasonal and monthly evaporation, wind speed and BSS

Evaporation, wind speed and BSS hours relate directly to atmospheric evaporative demand and evapo-transpiration (ET) of crops. They affect the stomatal opening and gas exchange through stoma and conspicuously govern crop phenology, growth and development (Mavi, 2001). Based on 29, 30 and 36 years durations, evaporation, wind speed and bright sunshine hours (BSS) exhibited significant ($p < 0.01$) declining annual (Fig. 2g–i), seasonal and monthly trends (Tables 3, 4). Annual mean evaporation (4.29 mm day^{-1}) varied in the range $3.78\text{--}5.24 \text{ mm day}^{-1}$. The highest seasonal mean evaporation (7.38 mm day^{-1}) was recorded for summer season followed by monsoon (4.42 mm day^{-1}) and winter (2.33 mm day^{-1}). The mean evaporation during different months indicated May to be the driest month (8.36 mm day^{-1}) and was followed by April (8.33 mm day^{-1}). There was continuous increase in the mean evaporation in months from January to May, followed by decline in December (1.61 mm day^{-1}). However, winter and summer months recorded a long-term decline in evaporation against no change or rising trend during June to October (Fig. 10). The rate of decline per decade in annual mean evaporation was 0.31 mm day^{-1} . This was corroborated by similar decadal decline rate for winter (0.30 mm day^{-1}) and almost double (0.56 mm day^{-1}) during summer seasons (Figs. 3e and 11d).

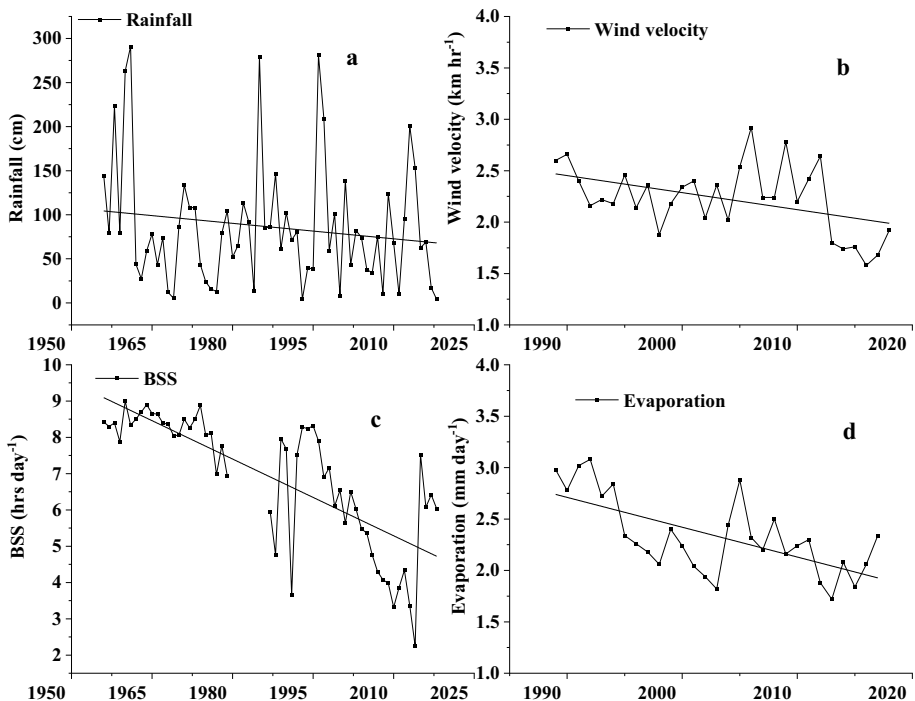


Fig. 12 Winter season trends for rainfall (a), wind velocity (b), BSS (c) and evaporation (d) during 1956 to 2018

Wind speed, an important climatic factor, exerts direct influence over gaseous exchange, rate of transpiration, light distribution in the canopy and impacts crop growth and productivity. Atmospheric stilling was evident with significantly declining annual, seasonal and monthly wind speed (km h^{-1}) over a period of 30 years (1989–2018). Annual mean wind speed (3.15 km h^{-1}) had inter-annual variation ranging between 2.51 and 3.81 km h^{-1} with a decadal decline rate of 0.29 km h^{-1} (Table 3). Our data show Gangetic plains of UP experience low to moderate winds during a year with highest wind speed (4.57 km h^{-1}) in summer season followed by monsoon (3.24 km h^{-1}) and winter (2.23 km h^{-1}) seasons. High evaporative demand during summer months (March–May) aggravates the irrigation needs and leads to lower cropping intensity during summers as compared to monsoon and winter seasons. This forces cultivation of short duration (60–75 days) pulses and vegetables only under assured irrigation availability.

Wind speed during different months gradually increased from January (2.70) to April (4.86 km h^{-1}), slowed down in the successive months till November (1.47) and again increased in December (1.77 km h^{-1}). Decadal change in monthly wind speed indicates significant stilling during (Fig. 12) January (-0.38 km h^{-1}), April (-0.38 km h^{-1}), July (-0.67 km h^{-1}), August (-0.42 km h^{-1}), September (-0.21 km h^{-1}) and November (-0.13 km h^{-1}). However, no conspicuous trend for average wind speed was observed for February, March, June, October and December that increased significantly with a decadal rate of 0.54 km h^{-1} in May (Table 4). This explained the sinking of ground water table in the region and extreme surface water scarcity in May and June. The long-term decline in wind speed during monsoon (Fig. 8c) and winter seasons (Fig. 11b) at respective decadal rate of -0.34 and -0.20 km h^{-1} , corroborates with downhill trend of precipitation during monsoon and frequent occurrences of mist and fog in the winters of Gangetic plains.

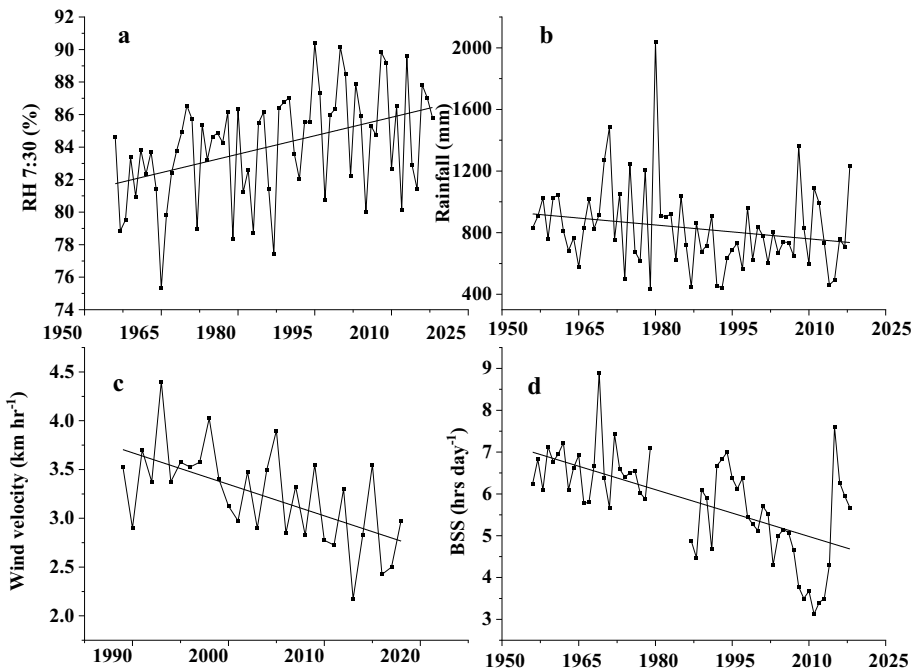


Fig. 13 Monsoon season trends for RH 730 hr (a), rainfall (b), wind velocity (c) and BSS (d) during 1956 to 2018

Bright sunshine duration regulates photosynthetically active radiation and metabolic responses of the plants. It determines the rate of plant growth, development and the variations in crop yield. The Gangetic plain of UP is endowed with sunny days throughout the year. The seasonal variation in BSS was within 6.37–9.01 h day⁻¹ for monsoon and summer. The average annual BSS (7.67 h day⁻¹) varied within 5.16–8.55 h day⁻¹ during 1982–2018 (Table 4). The long-term trend for 36 years indicated significant ($p < 0.01$) decadal decline in average annual BSS by -0.19 h day⁻¹ per decade (Fig. 2 g). This was due to sharp decline ($p < 0.01$) in winter (Fig. 11c) season (-0.29 h day⁻¹ per decade) and a moderate ($p < 0.05$) decline (by -0.17 h day⁻¹ per decade) during monsoon (Fig. 8d). A regular increase in BSS from January to May ranged from 7.28 to 9.29 h day⁻¹, which declined with the onset of monsoon in June (7.28 h day⁻¹) till September (6.76 h day⁻¹) and increased from October (8.18 h day⁻¹) till November (8.24 h day⁻¹).

The monthly long-term trend for BSS exhibited significant ($p < 0.01$) declining trend ranging from -0.22 to -0.40 h day⁻¹ reduction per decade during winters (November–February) (Table 4 and Fig. 12). This directly relates to increasing occurrence of severe cold and foggy days during these months and impact the crops adversely. BSS declined at the rate of -0.22 and -0.24 h day⁻¹ per decade in March and July, respectively, that coincides with grain filling stage of wheat in March and transplanting of rice in July. Singh et al. (2004) reported decline in global irradiance and increasing concentration of pollutants to be mainly responsible for declining evaporation and BSS. The decline in evaporation, wind speed and BSS with significant rate of decadal change shall cause emergence of new issues in relation to cropping system alterations, agronomic management of crops, disease, insect-pest dynamics and their management options.

3.2 Probable impacts of weather variability and adaptation strategies

Food, forage and vegetation production per unit area in any region is directly linked with climate change (Porter and Semenov, 2005). Understanding the relationship between crop productivity and weather variability in the region shall, therefore, help in enhancing the agricultural ecosystems resilience. The plain is the highest producer of food grains in India (Sehgal et al., 2013). About 78% of its population in 63 of 75 revenue districts in UP is engaged in cultivation of crops or animal rearing related enterprises and contributes about 51 million tonnes of food grains (Verma et al., 2017). However, with a population density (> 900 km⁻²) higher than most other agro-ecological regions of the world, size of land holdings in the region is fast becoming uneconomical and less suitable for technological advancements to adopt. Further burgeoning population and depleting soil fertility owing to loss of biodiversity make the region highly vulnerable to weather aberrations.

The climate change in the region across past decades is evident from wide range of annual, seasonal and monthly weather variability in temperature, rainfall, number of rainy days, relative humidity, wind velocity and bright sunshine hours. Since numerous crops are grown round the year, the variations in crop yields pose a serious threat to subsistence of the farmers. Fluctuations in crop yields are resultant of monthly, seasonal and annual weather variations, identifying the role of weather variability and designing adaptations strategies *vis a vis* use of fertilizer, irrigation, changes in land use patterns and crop rotations to minimize the associated adverse impacts. As the current trends of weather variability have significant impacts on crop growth and productivity, suitable adaptation strategies are the need of the hour. Our analyses of daily weather variables

during 1956–2018 have revealed rising trends in annual mean T_{\min} with no change in T_{\max} , indicating an increase in average temperature (Table 1). This coupled with sharp reduction (-28.97 mm decade $^{-1}$) in annual precipitation owing to significant decline in rains (Table 3) during monsoon season (-31.76 mm decade $^{-1}$) predict reduction in water availability, especially for agriculture that apports 77% of total water consumption in the Gangetic plains (Verma et al., 2017).

Temperature and precipitation are the most important weather factors that determine the cropping pattern, crop management practices, nutrient, water management and overall profitability from farm productivity. Rice and wheat, occupying about 10 million ha area each, face greater risk of shrinkage in area and loss of productivity owing not only to moisture stress, but also to unfavourable temperature at critical stages of growth. Trends in monthly T_{\max} , T_{\min} , rainfall and its distribution based on 63-years daily weather analyses evince that transplanting (middle of July–mid August) and initial growth of rice are set to face adverse impacts in view of rising T_{\max} (Fig. 3a) by 0.14 °C per decade, a decadal decline of 19.3 mm in rainfall and 0.48 number of rainy days in August. Profuse tillering in rice occurs after 4–5 weeks of transplanting which coincides with August. As Gangetic plains show a trend of rising mean temperature (> 29 °C at present), there may be reduced tillering in rice which shall affect the final crop stand and yield unless mitigated through adoption of suitable agronomic measures (Kannojiya et al., 2019; Mishra et al., 2013). The optimum temperature for profuse tillering in rice is 26 °C. Further, at temperatures higher than 26 °C, tillering stops in rice suddenly and takes long time to recoup even after putting back to the optimum levels again. During the various growth and development phases of rice, passing through September till December, increasing trend in morning RH (Fig. 4) and declining trends in evaporation (Fig. 12), wind speed (Fig. 12) and BSS (Fig. 9) might potentially influence the occurrence and spread of diseases viz., brown spot, bacterial leaf blight and neck blast and affect the rice productivity adversely. Barnwal et al. (2013) reported that changing climate variables conspicuously influence the disease occurrence in rice crop of South Asia. Further, enhanced CO_2 level per se leads to amplified severity of most of the diseases in various crops (Chakraborty et al., 2008). Severity of rice blast in Asian countries is set to go up under increasing temperature and humidity conditions (Luo et al., 1995). Considering the poor input supply like nutrients and paucity of rains as our analyses suggests, rice brown spot during ripening and maturity phase may potentially enhance the gap between attainable and actual yields in the Gangetic plains. Savary et al. (2005) reported enhanced severity of brown spot with increased occurrence of drought and rainfall aberrations. Insect-pests like borers, hoppers and sucking pests may also pose serious pest management challenges to crop productivity owing to the climate change (Lamichhane et al., 2015).

Cultivation and productivity of wheat, the second most important staple food crop of Gangetic plains, are at greater risk compared to rice, under current climate change trends. Growing season of wheat in the plain stretches from November (early autumn) till April (late spring). The period shows increasing trends in T_{\min} and RH (morning and afternoon), declining trends in evaporation, wind velocity, BSS, no change in monthly precipitation and number of rainy days. As successful wheat cultivation in the region depends on effective utilization of the post-monsoon moisture conserved in soil, large numbers of small and marginal farmers exploit this to ensure adequate germination. Verma et al. (2019) have reported that since rainfall is significantly declining during the monsoon months, with early withdrawal and current rising frequency of drought years, additional demand of water for pre-sowing irrigation in wheat would further worsen the

ground water situation (Table 1). Very little precipitation (86.17 mm) is received during wheat growing season in UP against the total water requirement of > 350 mm for the crop. This causes greater reliance of farmers on the ground water for providing 3–6 irrigations at the critical growth stages. Zaveri et al. (2016) reported that north-west India, specifically Gangetic plains of UP, suffered from unsustainable ground water extraction, indicating insufficient recharge from precipitation and surface water resources. This might lead to sinking of ground water beyond the reach of large number of poor wheat growers and cause loss of 0.2–0.5 million tonnes of annual food grain.

Further, the significant rising trend of T_{\min} in the region during February (0.33 °C) and March (0.29 °C per decade) coincides with grain filling and maturity stages of wheat crop. This causes adverse impacts on the average grain weight and leads to severe yield loss. Elevated temperature during anthesis to grain maturity reduces the grain yield owing to reduced capturing of resources (Wheeler et al., 1996). Climate change induced yield reduction in wheat was estimated to be 88.2 kg ha⁻¹ (Mitra & Bhatia, 2002). A loss of 12 to 29% of wheat yield has been reported owing to enhanced temperature levels up to 1–3 °C above normal. Kannojiya et al. (2019) and Kaur and Hundal (2006) attributed the yield losses to decrease in number of spikes m⁻², number of grains per spike and test weight. Wheat varieties currently being developed in the Gangetic plains need to carry traits for producing heat shock proteins to maintain membrane conductivity and photosynthesis at elevated temperatures. Agronomic measures for ensuring early sowing to escape the terminal heat by adjusting the cropping systems and water efficient measures need to be adopted, to keep off the yield reduction. Conservation tillage techniques like zero tillage including wheat sowing in standing rice residue, residue recycling and sowing of wheat on broad beds for better utilization of applied inputs need to be popularized among growers to stave of negative impacts of changing climate.

Agrarian economy of the Gangetic plains gets regulated by the income obtained from the only industrial crop of the region, sugarcane. The earnings from sugarcane crop are often ploughed back for supply of critical inputs to other crops, especially rice and wheat. For this reason, profitable sugarcane cultivation makes the foundation for overall farm prosperity of the Gangetic plains. Its year long duration, high inputs, greater water requirement and labour needs, makes it pivotal component of all the cropping systems and rotations adopted in the region (Srivastava et al., 2013). Planted in the months of February–March, the crop is harvested after 10–12 months of planting and faces ample weather variations during all three seasons. A varied climate suitability need of sugarcane during growth phases renders it to bear the adverse impacts of changing climate to a greater extent compared to the other crops. Germination phase that requires warm and dry climate happens during February–March (spring season) is facing significant rising trend in T_{\min} and RH, no change in precipitation, wind speed and declining trends in evaporation and BSS (Figs. 5e, f, 6b, c, 7b, c, 9b, c, 10b, c, 13b, c). As such the climatic conditions still hold good for sugarcane planting in spring season and there is no threat to adequate crop stand as far as germination is concerned. However, with rising RH, infestation with insect-pests like early shoot-borer (*Chilo infuscatellus* Snellen.) and top-borer (*Scirpophaga excerptalis* Walker.) has been observed to be increasing during early germination and initial tillering stages. Use of resistant varieties and clean cultivation techniques need to be widely adopted to avoid excessive chemical application. Further, tillering, the underground sprouting of side buds located on new emerged shoots thrives under adequate soil moisture availability in hot and dry climate that prevails during summer months (April–mid June). Our analysis found that except for significant rise in morning and afternoon RH, corroborated

by conspicuous decline in evaporation and wind speed, other weather parameters remain favourable. Rising levels of RH are congenial for borer-pest infestations that hinder tillering and reduce number of millable canes and yield. This might hamper the wider row (> 120 cm) sugarcane planting currently being promoted to reduce seed expenditure and increase mechanization in sugarcane.

Development of high tillering varieties and precision nutrient management is the suitable options under such a scenario. The crop has high irrigation requirement, and in the absence of rains, surface or ground water is utilized by the farmers unabashedly that worsens the already strained ground water situation. Microirrigation techniques like surface and sub-surface drip irrigation, fertigation and use of sugarcane dried leaves as bio-mulch have the potential to save 30–50% of total irrigation requirement of the crop with additional benefits of weed suppression and soil health improvement (Srivastava et al., 2011). The grand growth phase, with longest duration between 130 to 270 days after planting that contributes about 85% of total crop biomass production, coincides with onset of rainy season. The phase is set to face severe stress due to frequent occurrence of drought, late start of rainy season and significant decline in rainfall ($-31.76 \text{ mm decade}^{-1}$) (Attri & Tyagi, 2010). Water application through irrigation fails to create ample humidity to trigger cane elongation leading to conspicuous loss of cane length that is known to contribute about 27% towards cane yield (Singh & Rai, 2018; Yadav & Sharma, 1978). Further, there is tough competition for available irrigation water as rice being the main staple food crop gets priority for irrigation at the cost of other important crops. Development of moisture stress tolerant and high water use efficient varieties of sugarcane is, therefore, imperative to reduce the adverse impact of declining rains in the region. Government policies to support adoption of water efficient drip irrigation techniques to save up to 30% of the total water requirement of sugarcane crop with additional input use efficiency and cane yield are among strong imperatives. The state of UP in collaboration with the Government of India is implementing National Mission on Sustainable Agriculture that among other schemes also promote drip irrigation among resource poor farmers by bearing up to 60% of the total expenditure since 2015. About 50,000 ha in UP has come under this scheme and holds promise to make farming more resilient for climate change (UPSAPCC, 2014).

Ripening and maturity of sugarcane crop during October–February (winter season) might face adversities in view of significant rise in T_{\min} , morning and afternoon RH coupled with significant decline in T_{\max} , daily evaporation, wind speed and BSS with no alteration in seasonal rainfall. Rapid sugar accumulation that is favoured under cold and dry climatic conditions gets adversely impacted by the climate change. Thus, varieties with high sugar accumulating trait during narrow variation in diurnal temperature, reduced sunshine hours and enhanced humidity levels need to be adopted at large scale. Adoption of such new varieties CoLk 94184 and Co0238 stand to testimony of concept as sugar mills having coverage with these varieties have increased sugar recovery (<http://upcane.gov.in>). Water availability and labour are two major factors that determine cropping system of any geographical region. Gangetic plains of UP, with 65% of its population engaged in agriculture, still enjoys ample labour availability in addition to fast mechanization for reducing drudgery and enhancing human efficiency. However, a general lack of rural roads, distant input markets, irregular electricity supply and meagre public infrastructure for seed and grain storage render the Gangetic plains vulnerable to climate change manifesting as rising daily temperature and significantly declining annual rainfall. Under the scenario, alterations in present cropping system dominated by high water requiring staple food crops, need to be diversified with high value, less water requiring crops like coarse grains, pulses and oilseeds. To raise the level of nutritional security, greater area may be brought under

fruit orchards with drip irrigation. As agronomic management of field crops still remains favorable for the prevalent crops in IGP, the major emerging crisis is sustenance of crops under declining precipitation and ground water availability. In situ surface water harvesting facilities are required to be strengthened at village/development block level supported with ground water recharge and water efficient irrigation techniques.

4 Conclusions

Gangetic plain of UP is richly endowed, densely populated and agriculturally important geographical region of India. It supports livelihood of 119 million people besides copious contribution to Indian granary. Rice and wheat are grown in almost 70% of net cultivable area in rotation with sugarcane, the only industrial crop of the region, along with pulses, oilseeds, and vegetable and forage crops in year-long growing season. Weather, which plays crucial role in determining the productivity and profitability of agriculture, is facing wide fluctuations in view of increasing frequency of aberrations and extremes like droughts, cyclones and heavy rains. Owing to small and fragmented land holdings and general lack of farm related infrastructure, the region stands moderate to highly vulnerable to climate change impacts. Conspicuous long-term (1956–2018) trends of reduction in annual rainfall (-28.97 mm decade $^{-1}$), rising level of daily T_{\min} (0.09 °C a decade) and RH (1.08% decade $^{-1}$) coupled with significant declining trends in evaporation (-0.31 mm day $^{-1}$), wind speed (-0.29 km h $^{-1}$) and bright sunshine hours (-0.19 h day $^{-1}$) elucidate the climate change pattern over the region poignantly. Impact of weather variability and climate change on agriculture is evident with wide fluctuations of rice and wheat annual yield ranging within -15.76 to 30 per cent during the period in different districts of the region. Precipitation decline has led to surface water shortage and insufficient ground water recharge. This does not auger well for sustaining the crop yield and profitability in the plain as crop management of the prevailing cropping systems relies heavily on water through irrigation at low field application efficiency ($<40\%$). Multi-pronged strategies comprising development of water efficient crop varieties, cropping system diversification with less water requiring crops, adoption of water efficient irrigation techniques, surface water harvesting and copious ground water recharge are needed for adoption immediately. Survey and surveillance of disease pest occurrences in different crops under the changing climate are also needed to minimize the yield loss and to ward off any new insect-pest or disease in the present climate scenario.

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