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L E T T E R S

551.583 ; 551.509.331 (540.15)

ANALYSIS AND MAPPING OF SPATIO-TEMPORAL CLIMATE VARIABILITY IN PUNJAB USING CLASSICAL STATISTICS AND GEOSTATISTICS

1. Climate change is an undeniable fact, which is altering the temporal and spatial distribution of crops and water resources, having a significant effect on society, economy, and ecology, thus arousing the increasing attention from scientists, policy makers and governments in every country (Yunhe *et al.*, 2010 and IPCC, 2007). During the period 1885-2012, average global temperature has increased by 0.85 ºC and is predicted to increase further by 1.6-5.8 ºC by the end of 21st century (IPCC, 2014). Climate change is expected to alter climate variability (Senevirante *et al.*, 2006; Meehl *et al.*, 2007), increasing the frequency and intensity of precipitation events (Alexander *et al.*, 2006; Kunkel *et al.*, 2008) as well as extreme temperatures (Duffy and Tebaldi, 2012). Climate change triggered extreme weather events are creating imbalances in hydrological cycle and large year-to-year fluctuations in crop yields and water productivity in the recent years (Lal *et al.*, 1998; Singh *et al.*, 2013; Dwivedi *et al.*, 2013).

Agriculture is considered as the most weather-dependent human activity (Hansen, 2002). Many studies indicate a probability of 10%-40% loss in Indian food grain production due to increase in temperature by 2080-2100 (IPCC, 2007; Fischer *et al.*, 2002; Parry *et al.*, 2004). The threat of climate change is affecting and will affect the important natural resources including water. Due to climate change, the spatial and temporal distribution of rainfall is expected to vary a lot (Oki and Okane, 2006). The rising temperatures may increase evaporation rates. This coupled with variable rain distribution could lead to variations in water availability and ground water recharge (Huntington, 2005). To manage this alarming situation, there is a need to analyse the spatio-temporal variability in climatic patterns at regional scale, so that viable mitigation / adaptation strategies can be developed in spatial domain and implemented on regional basis.

The state of Punjab, covering North-Western parts of Indo-gangetic plains in India, is also experiencing large fluctuations in temperature and precipitation patterns every year leading to large oscillations in agricultural productivity in the region [Kingra, 2016 (a&b)]. Annual maximum and minimum temperature in Punjab are expected to increase by 2-3 ºC by 2020-2050 (Jalota and Kaur, 2013). Most of the previous studies have analysed the data for few districts in Punjab using linear regression. Kaur *et al.* (2013) analysed the climate data of six locations in Punjab using linear regression analysis and found a significant increase in minimum temperature and no-significant changes in maximum temperature. Kingra [2016 (a&b)] analysed the long-term meteorological data during growing period of rice and wheat crops for central Punjab, but these studies used the linear regression to detect the trend in climate parameters and did not use any spatial interpolation technique for climate characterization which is useful for making long-term planning of judicial use of resources under future climate change. Parametric

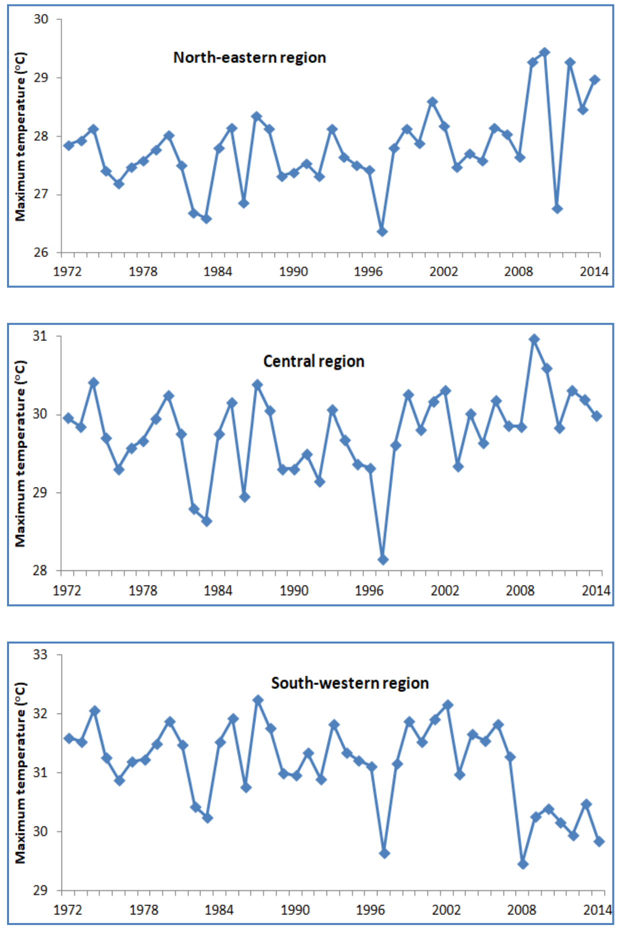

Fig 1. Long-term variability in mean annual maximum temperature in different regions of Punjab

TABLE 1

Results of the statistical tests for mean annual climatic parameters over the four decades in different regions of Punjab

Zone		1974-75 to 1983-84	1984-85 to 1993-94	1994-95 to 2003-04	2004-05 to 2013-14	1974-75 to 2013-14
Maximum temperature (ºC)						
North-east	Mean±SD	27.8±0.5	28.1±0.5	28.1±0.4	28.5±1.3	28.1±1.0
	Z	-0.894	-0.179	1.252	1.073	2.575*
	Q	-0.090	-0.007	0.095	0.111	0.021
Central	Mean±SD	29.7±0.7	29.9±0.7	29.9±0.7	30.4±0.5	29.6±0.7
	Z	-1.073	-0.537	1.073	0.537	2.016*
	Q	-0.093	-0.036	0.083	0.033	0.016
South-West	Mean±SD	30.9±0.4	31.2±0.4	31.0±0.4	30.5±0.3	29.1±0.4
	Z	-1.073	-0.537	0.894	-1.789+	-1.433
	Q	-0.091	-0.034	0.091	-0.214	-0.017
Minimum temperature (ºC)						
North-east	Mean±SD	14.7±0.4	14.8±0.5	15.3±0.5	16.6±0.6	15.5±0.6
	Z	0.358	0.000	1.789+	1.610	5.255***
	Q	0.019	-0.013	0.089	0.285	0.051
Central	Mean±SD	15.8±0.3	16.0±0.7	16.4±0.5	18.6±1.6	16.7±0.8
	Z	1.789+	0.179	2.504*	1.073	5.511***
	Q	0.117	0.040	0.146	0.041	0.050
South-West	Mean±SD	16.3±0.1	16.6±0.2	17.0±0.1	18.7±2.6	17.2±8.6
	Z	1.252	-0.179	1.431	1.073	5.301***
	Q	0.066	-0.025	0.100	0.071	0.047
Rainfall (mm)						
North-east	Mean±SD	938.1±106.4	971.7±85.1	1054.6±115.1	887.1±67.6	962.9±93.55
	Z	1.073	-0.716	-2.326*	-0.537	-0.245
	Q	1.382	-1.459	-5.452	-1.169	-0.069
Central	Mean±SD	676.4±177.8	675.5±182.2	772.6±138.3	691.0±112.3	703.9±152.7
	Z	1.073	-0.358	0.179	-0.537	0.384
	Q	1.104	-0.672	0.567	-1.588	0.070
South-West	Mean±SD	410.2±28.7	429.4±53.5	424.4±54.8	427.1±36.0	422.8±43.3
	Z	-0.537	-0.179	-1.610	0.716	0.641
	Q	-0.595	-0.563	-1.694	1.380	0.105

Z: Mann-Kendall test, Q: Sen's slope estimator.
* Statistically significant trends at the 5% significance level, ** Statistically significant trends at the 1% significance level, *** Statistically significant trends at the 0.1% significance level

test (like linear regression) requires that data should be normally distributed and independent, whereas the non-parametric test (like Mann-Kendall and Sen's methods) requires only that the data should be independent. We used the Mann-Kendall and Sen's methods, and inverse distance weighting technique to study the spatio-temporal analysis of rainfall and temperature over a period of 40 years in Punjab.

2. The study area is located in North-West Indo-Gangetic plains of India, which is the most feasible region with respect to agricultural production of the country, generally termed as 'food bowl' of India. The state of Punjab, covering 1.5% (5.03 million hectare) geographical area of the country, is characterized by sub-tropical, semi-arid type of climate with three distinct seasons namely hot

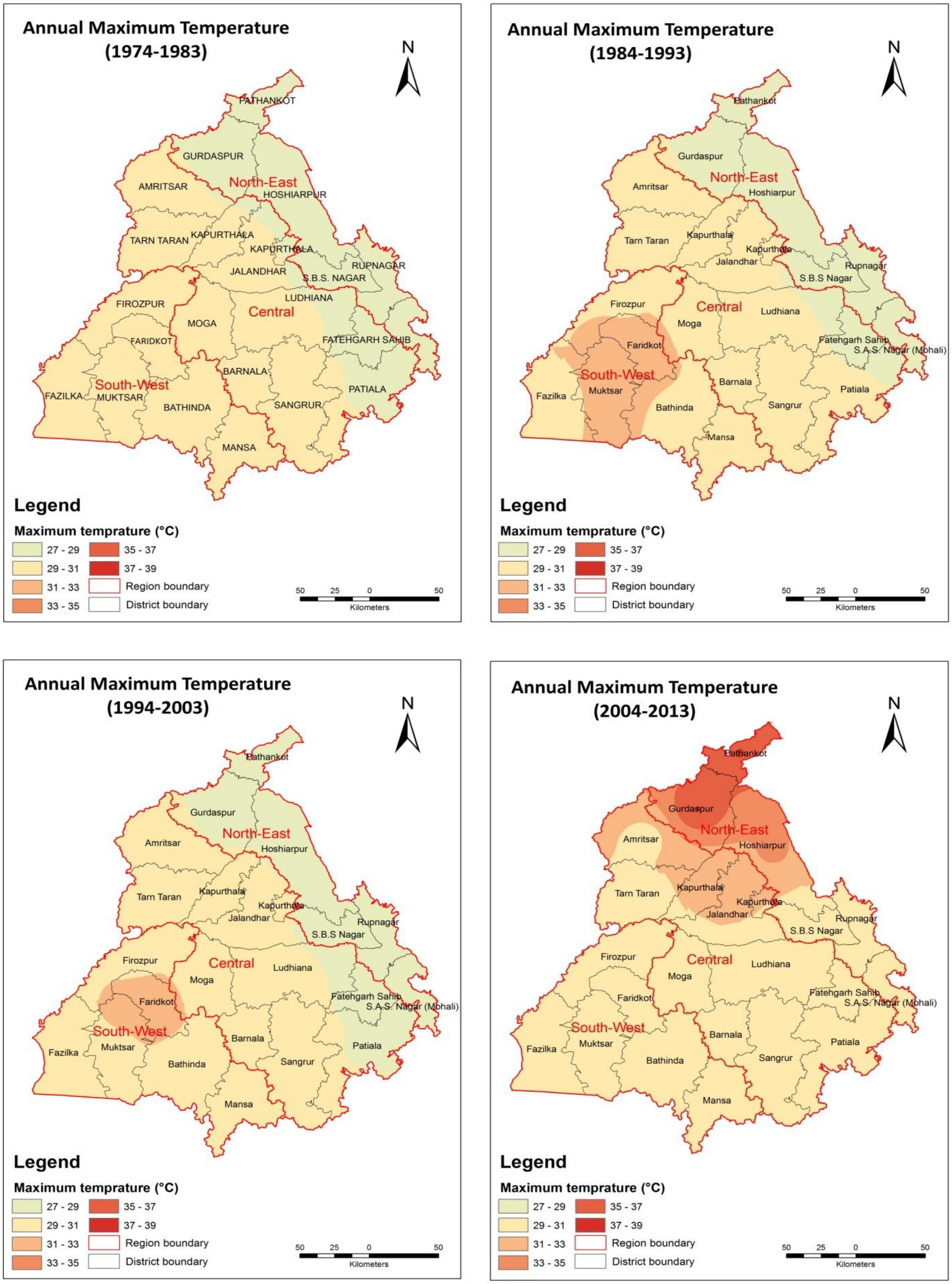

Fig. 2. Spatio-temporal variability in annual maximum temperature in Punjab

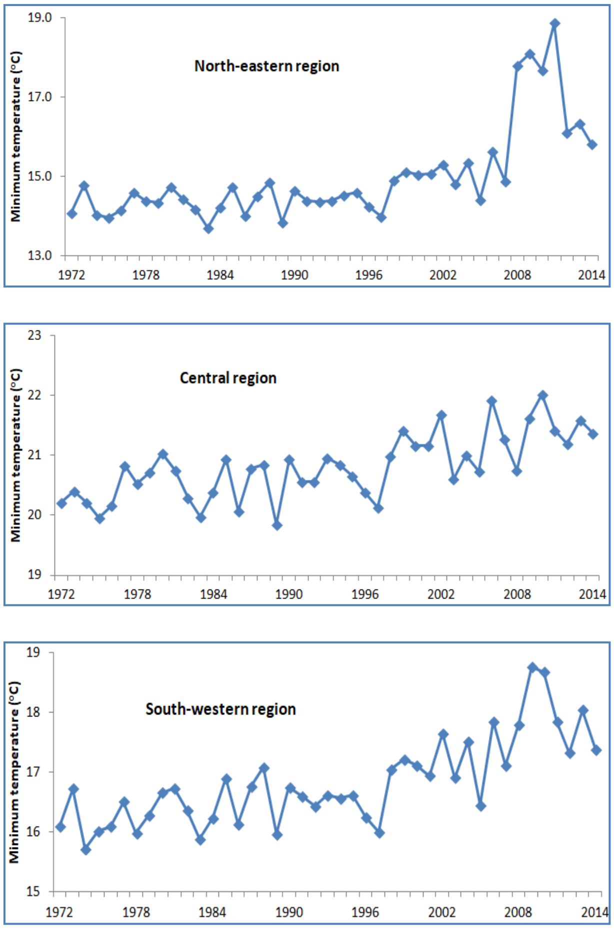

Fig 3. Long-term variability in mean annual minimum temperature in different regions of Punjab

and dry summers (April-June), monsoon (July-September) and cold winters (Dec-Feb). The minimum temperature in the state can be as low as 0 °C or even lower (January), while the maximum temperature can be as high as 45-46 °C (June). Punjab being a very small state, has very narrow range of both latitudinal and longitudinal extent to the tune of 29° 33′ N - 32° 31′ N and 73° 55′ E - 76° 55′ E, respectively. Based on the climatic variability in different regions, the whole state was divided into three regions: Northeast, Central and Southwest.

The data of maximum temperature, minimum temperature and rainfall for different districts was collected from different sources like Agrometeorological observatory, School of Climate Change and Agricultural Meteorology, Punjab Agricultutral University (PAU), Ludhiana; different regional research stations of PAU, India Meteorological Department (Chandigarh) and various issues of statistical abstracts of Punjab.

Long-term variability and trends of mean annual maximum temperature, minimum temperature and rainfall were studied on annual basis over different decades (1974-83, 1984-93, 1994-2003 and 2004-2013) for the three regions of the state. Two non-parametric methods (Mann-Kendall and Sen's slope estimator) were also used to detect the meteorological variables' trends. Mann-Kendall test evaluates whether meteorological values tend to increase or decrease over time. The Mann-Kendall test analyzes the sign of the difference between later-measured data and earlier-measured data (Meals *et al.*, 2011). Each later-measured value is compared to all values measured earlier, resulting in a total of n (n-1)/2 possible pairs of data, where n is the total number of observations. In this test, the difference between the later-measured value and all earlier-measured values, (y_j-y_i), where j>i, is calculated. The test statistic, S, is then computed as the sum of the integers:

where, sign (y_j-y_i) is equal to -1, +1 or 0. The variance associated with S is calculated from the following equations:

$$V(S)=\frac{n(n-1)(2n+5)-\sum_{k=1}^{m}t_k(k-1)(2t_k+5)}{18}$$

where, m is the number of tied groups and t_k is the number of data points in group k. The standardized Mann-Kendall test statistic Z which follows the standard normal distribution with mean of zero and variance of one is given by:

$$Z=\begin{cases}\dfrac{S-1}{\sqrt{V(S)}} & for\ S>0\\ 0 & for\ S=0\\ \dfrac{S-1}{\sqrt{V(S)}} & for\ S<0\end{cases}$$

When the Z values computed by above equations are greater than the critical values of Z at a given level of significance, the null hypothesis (no trend in the data) is rejected. The positive values of S indicate an increasing trend, the negative values a decreasing trend and the smaller values no trend. If a significant trend is found, the rate of change can be calculated using the Sen slope estimator (Helsel and Hirsch, 1992).

$$Q=median\left(\frac{y_j-y_i}{X_j-X_i}\right)$$

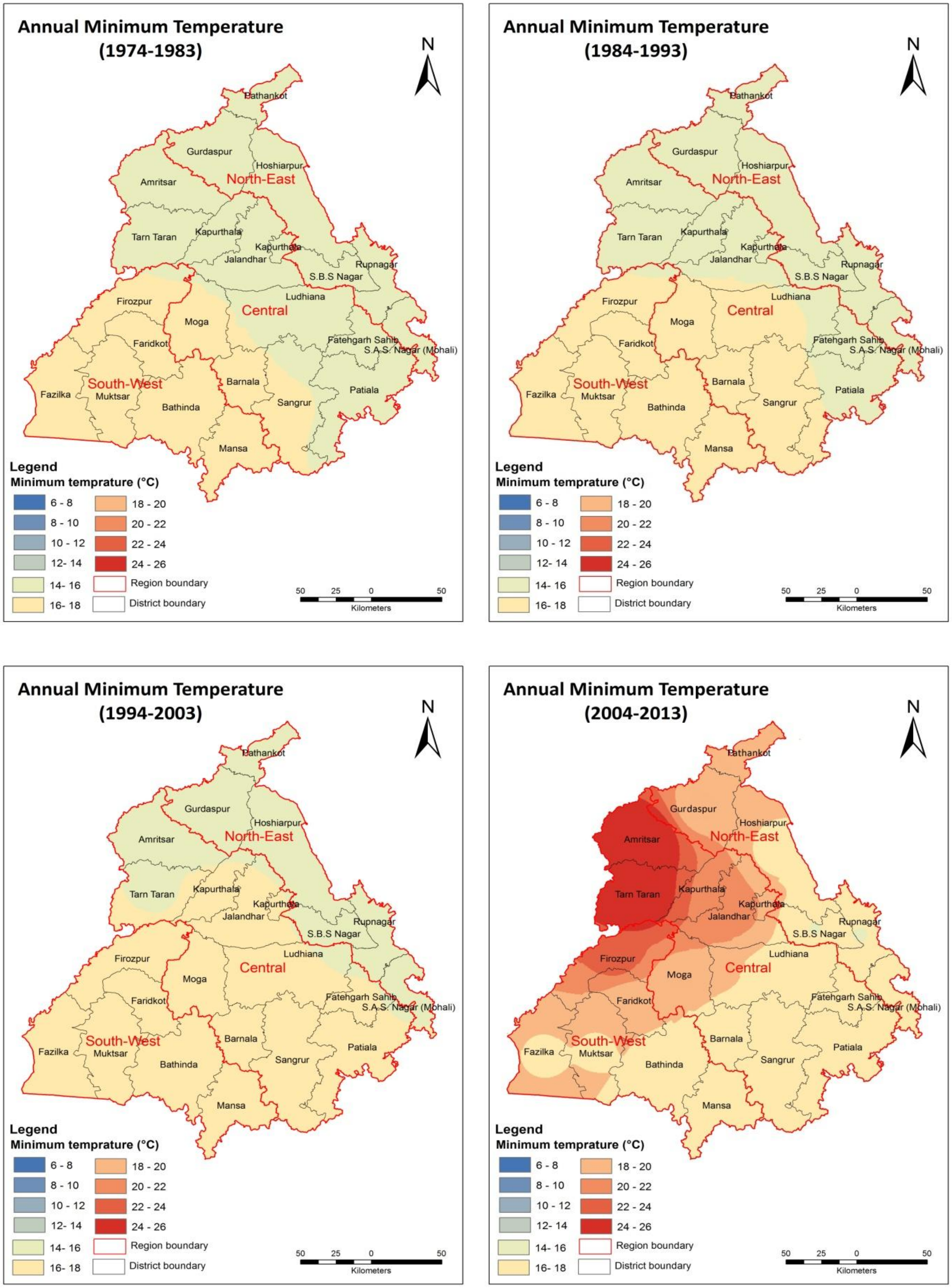

Fig. 4. Spatio-temporal variability in annual minimum temperature in Punjab

for all $i < j$ and $i = 1, 2, \ldots, n\text{-}1$ and $j = 2, 3, \ldots, n$;. The median of those slopes is the Sen slope estimator.

The annual spatio-temporal variability of temperature and rainfall over different decades (1974-83, 1984-93, 1994-2003 and 2004-2013) in Punjab was studied using Inverse Distance Weighted (IDW) Method in Arc GIS 10.2.

3. Average annual maximum temperature increased from 27.8 ºC during 1974-83 to 28.5 ºC during 2004-13 in the north-eastern Punjab and from 29.7 during 1974-83 to 30.4 ºC during 2004-13 in the central Punjab. There were large annual fluctuations in maximum temperature in all the regions of Punjab (Fig. 1). In the south-western region, it increased from 30.9 ºC during 1974-83 to 31.2 ºC during 1984-93, but decreased thereafter to 30.5 ºC during 2004 - 2013 (Table 1). Decade-wise trend analysis using Mann-Kendall test and Sen's slope estimator showed a no significant trend in maximum temperature over different decades in the three regions of Punjab. Spatially maximum temperature increased from 27-29 ºC to 31-37 ºC over 40 years in the north-east region of Punjab and from 27-29 ºC to 31-33 ºC over 40 years in the central region of Punjab (Fig. 2).

Decade-wise analysis of average annual minimum temperature showed that it increased from 14.7 ºC during 1974-83 to 16.6 ºC during 2004-13 in the north-eastern region, whereas it increased from 15.8 to 18.6 ºC in central, 16.3 to 18.7 ºC in south-west and 15.6 to 18.1 ºC in the entire state for the corresponding period (Table 1). In general, minimum temperature increased over the years in all the regions of Punjab (Fig. 3). Decade-wise analysis using Mann-Kendall test and Sen's slope estimator showed a significant increase in minimum temperature in all the regions and the rate of increase was approximately 0.05 ºC $year^{-1}$ in the three regions of the state. Spatially increasing pattern of minimum temperature was observed from north-east to south-west. Mean annual minimum temperature increased from north-east to south-west region of Punjab. Spatially minimum temperature increased from 14-16 ºC to 18-20 ºC over 40 years in the north-east region of Punjab and from 14-16 ºC to 24-26 ºC over 40 years in the central region of Punjab and from 16-18 ºC to 22-24 ºC over 40 years in the south-west region of Punjab (Fig. 4).

Average annual rainfall in Punjab increased from 1974-83 to 1994-2003 in the North-East and central region, but decreased in the recent decade (2004-13). No significant variation was observed in rainfall in the south-west region (Table 1). In the north-eastern region, it increased from 938 to 1055 mm during 1974-83 to 1994-2003, but it decreased to 963 mm during 2004-2013. In

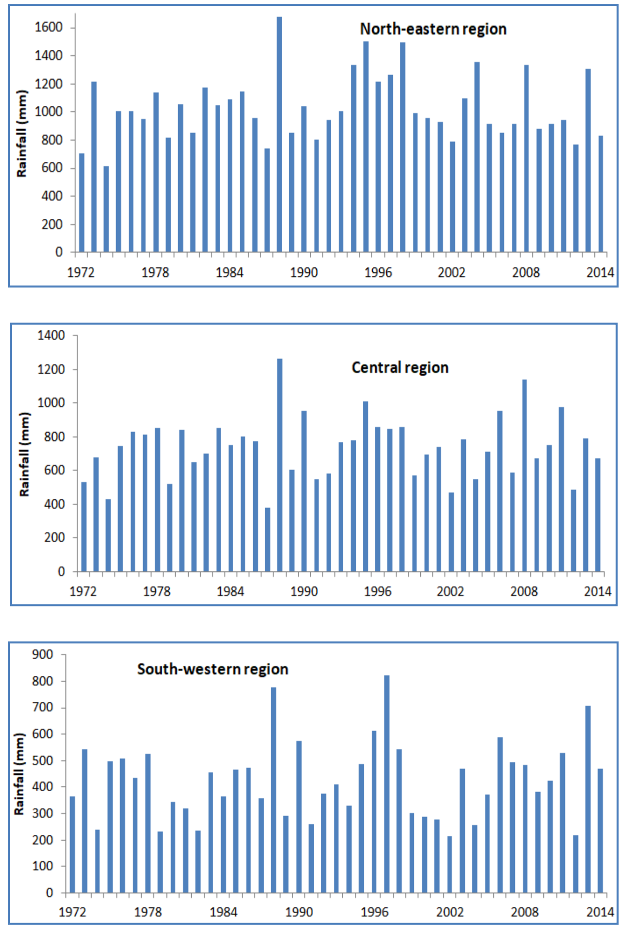

Fig 5. Long-term variability in mean annual rainfall in different regions of Punjab

the central region, annual average rainfall increased from 676 to 773 mm during 1974-83 to 1994-03 and decreased thereafter to 691 mm during 2004-13. In the south-western region, annual average rainfall increased from 410 to 429 mm during 1974-83 to 1984-93, then decreased to 424 mm during 1994-03 and thereafter increased to 427 mm during 2004-13. No significant trend was observed in rainfall pattern in the state indicating highly erratic nature of rainfall, but a critical analysis indicated large annual fluctuations in all the regions (Fig. 5). There was a significant spatial variation in rainfall in the state. Spatially a decrease in annual rainfall was observed from north-east to south-western Punjab (Fig. 6).

4. Trend analysis and spatio-temporal variations in temperature showed an increasing trend over the years. Increasing temperature can have detrimental effect on crop productivity as it increases rate of respiration and decreases net photosynthesis, thus resulting in reduced crop productivity (Kingra, 2016a; Rao *et al.*, 2015). The

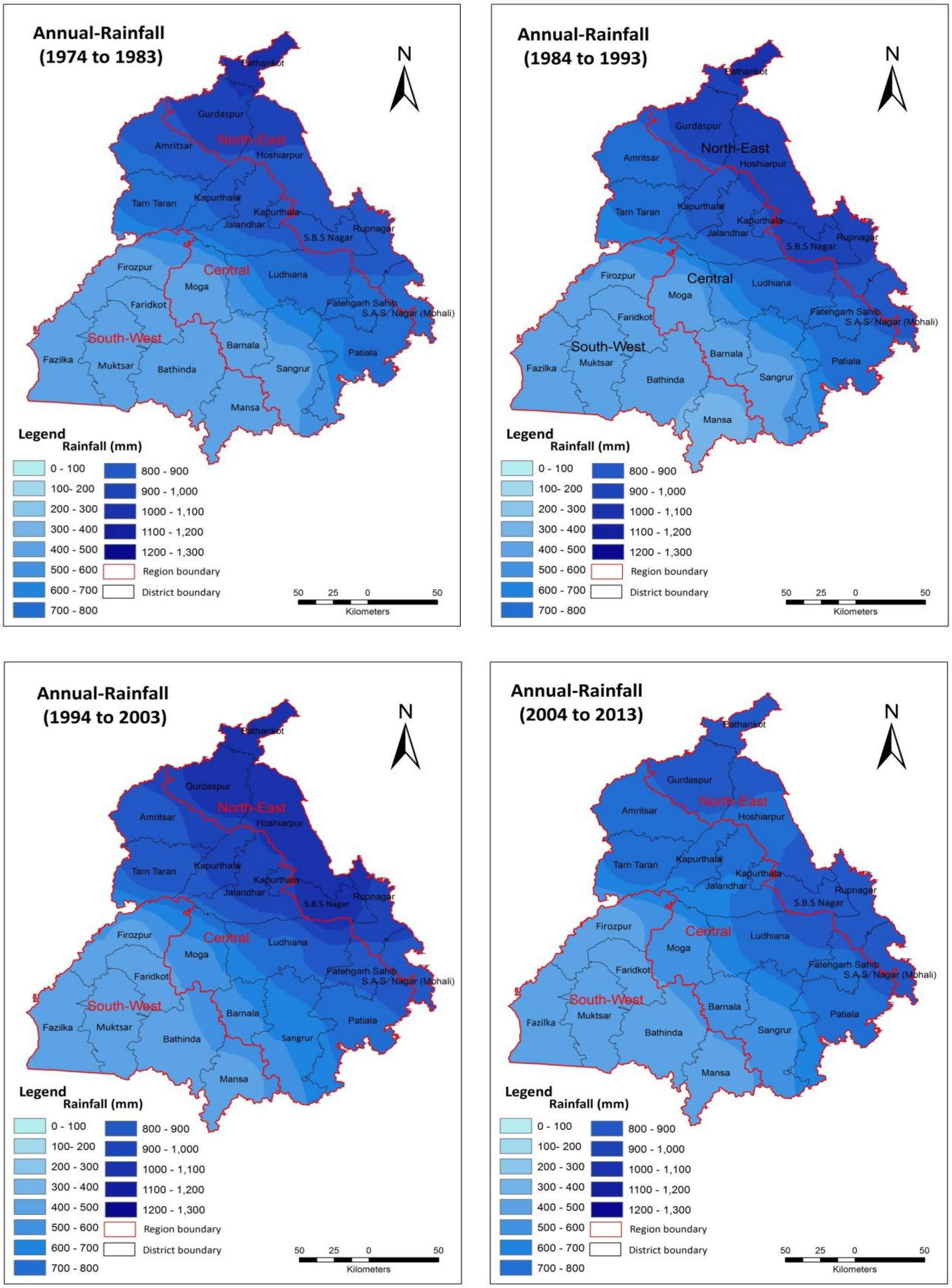

Fig. 6. Spatio-temporal variability in annual rainfall of Punjab

decrease in rainfall during the recent decade is indicating about the alarming situation of water availability in the region. As the ground water resources are already over-exploited (Hira, 2009), thus erratic and decreasing pattern of rainfall can further aggravate the severity of the situation in addition to its adverse impacts on crop productivity. If an increase in temperature continues, it can have adverse impact leading to the extinction of many species of flora and fauna. Human and animal life may also be serving a death sentence, if the trend is not checked. Such climatic changes will have far reaching effects on animal and human life including melting of glaciers and polar ice caps, rise in sea level, changes in rainfall pattern and extreme weather events, impact on natural ecosystems, agriculture, food security, livestock production, industry, human comfort and health. Since Punjab is an agrarian state, the potential effects of climate variations on agriculture and livestock have been discussed below:

(*i*) Global warming has increased the global temperatures which adversely affect the crop growth. The most common types of natural disasters that negatively impact food supply chains are drought, floods, storms, frost and high winds (Johnson, 2003). Changing climatic conditions are also affecting the availability and utilisation of nutrients by the crops. Increase in minimum temperature under Punjab conditions is adversely affecting tillering and yield in wheat crop. It has been observed that the yield of wheat crop is highly influenced by weather conditions especially during February and March. Kingra (2016a) reported that lower minimum temperature, lower morning relative humidity and less rainfall as well as number of rainy days during the reproductive growth period of the crop are most conducive for achieving higher yields of wheat. All these conditions were observed during 2011-12, hence record yield of 5.38 Mg ha^{-1} was observed, whereas during lowest yielding year of 2008-09 maximum temperature, minimum temperature, morning relative humidity and number of rainy days were higher than normal, hence crop yield decreased. After obtaining record wheat yield in 2011-12, weather conditions again reverted in 2012-13 with above normal minimum temperature, relative humidity, rainfall and number of rainy days during reproductive growth period of the crop and hence the wheat yield decreased. Such impacts of climate change can have severe implications on food security in the coming years. In the near future, intensified heat can reduce crop duration, increase crop respiration rates, accelerate nutrient mineralization in soils, decrease fertilizer use efficiency and increase evapo-transpiration. All these will have an adverse impact on crop yields with productivity fluctuating considerably. Since the crops are already near their maximum heat tolerance, added heat stress and other problems like shifting monsoons, extreme weather events (like drought, floods, tropical cyclones, heavy rainfall, heat and cold waves) may reduce the yields especially in the tropics and sub-tropics.

(*ii*) The climate change has a great impact on livestock of any region. Climate change affects livestock production mainly due to its impact on feed quality, quantity, heat stress, water availability, livestock diseases and disease vectors as well as biodiversity including herbage and pasture composition. Hopkins and Del Prado (2007) reported that climate change will have several impacts on feed crops and grazing systems including changes in herbage growth and quality due to changes in CO_2 concentration and temperature. Warming alters heat exchange between animals and environment, feed intake, mortality, growth, reproduction, maintenance and production. Heat stress declines physical activity, feed intake and milk production. It also decreases cow fertility, fitness and longevity. Nardone *et al.* (2010) reported that hot environment impairs production (growth, meat and milk yield and quality, egg yield, weight and quality) and reproductive performance, metabolic and health status, and immune response. Efficient livestock production systems under increasing temperature and extreme events require better information regarding biophysical and social vulnerability and this must be integrated with agriculture and livestock components.

5. Large spatio-temporal variation has been observed in annual temperature and rainfall pattern of Punjab. Significant decrease in rainfall and increase in temperature is observed from north-east to south-western Punjab. Although no significant trend has been observed in rainfall pattern in the state, but large fluctuations are indicating its highly erratic nature calling for more careful and efficient planning of water resources in the region. However, significant increase in temperature pattern observed in different regions of the state warns about more warming scenarios in future which can have adverse effects on crop productivity in the region, thus indicating a dire need of climate smart adaptation and mitigation strategies for sustaining crop productivity and achieving food security under changing climatic patterns in the region.

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