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PUNJAB AND HIMACHAL PRADESH: TEMPERATURE VARIABILITY AND TRENDS SINCE 1900 AD

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Abstract

Drastic temperature changes have taken place during the last century and are expected to increase critically before the end of 21st century. The predicted changes might be more worrisome for certain regions such as north-western India wherein temperatures are projected to escalate at alarming rates. This research paper examines the long-term variability and trends of temperature in Punjab and Himachal Pradesh located in north-western parts of India. The results reveal striking facts about the direction and magnitude of change. The cooling of Punjab Plains during summer, post-monsoon and monsoon season is evident whereas mountainous areas of Himachal Pradesh exhibit warming in almost every season. These warming rates are most conspicuous in the Middle and the Greater Himalayan regions. The warming of winter and post-winter seasons, especially in temperate and cold semi-arid/arid regions of Himachal Pradesh raises serious concerns about impending critical water stress and disruption of hydrological balance upon which rests the economic development of the study area.

Introduction

The reality and repercussions of climate change are as startling as it is a contentious process. Temperature being a major controlling factor of ecosystem has directed the distribution and evolution of life on the earth. Earth has undergone staggering changes in temperature conditions in its geological past. Holocene epoch (c. 11,700 BP) is considered to be a relatively balanced phase with least climatic fluctuations. However, even in this phase of near equilibrium, some minor temperature deviations have had decided impacts on humankind. The time period from 7000-5000 BP was warmer than the present but last 5000 years have been marked by a declining temperature with exceptionally cold phases at about 2800 and 350 years ago (IPCC, 2007a). These climatic swings in the past 3000 years had a close association with the disruption of many civilizations across the globe (Hodell et al., 1995; Curtis et al., 1996; deMenocal, 1999, 2001; Welc and Marks, 2014).

The past century has recorded maximum changes in temperature conditions on land and sea surfaces; sea level rise, oceanic acidification and changes in the cryosphere have taken place at unprecedented rates in the recent 1300 years (IPCC, 2007b, 2013). The average global temperature has increased by 0.65°C to 1.06°C in the past 150 years (IPCC, 2015) which is likely to increase further by

1.8°C to 4°C before the end of 21st century. Such temperature increases have induced rapid retreat of glaciers in mountainous regions (IPCC, 2007a) and there is a definite reduction in the extent and thickness of Arctic sea ice (Polyak et al., 2009). The direction of climate change has not been uniform; the period from 1880-1940 witnessed an increase in temperature followed by a decline during 1940-70, while post-1970s is a period of remarkable warming (Parkinson, 2010). The surface air temperature and sea surface temperature have increased substantially in last 100 years (Martinez et al., 2007).

The magnitude of warming over India is analogous to global trends (Pant and Kumar, 1997; Arora et al., 2005). In the last 100 years, temperature has increased by 0.68°C and warmest daily maximum temperatures are projected to escalate by 4°C to 5°C with maximum increase in northern and western India, while southern parts of India will face the maximum increase in tropical nights by the end of 21st century (IPCC, 2013). Studies on regional and local scales show that there is an increase in diurnal range of temperature (Tigga and Malini, 2011). The seasonal and annual temperatures particularly in winter season (Singh et al., 2011; Chatranta and Sharma, 2013; Thakur et al., 2016) has increased over the time indicating warming. These observed trends show varying degree of regional patterns and are likely to cause aridity in some regions , while some other areas will become wetter and hotter (Dai, 2013).

The evidences for climatic changes are ample and worrisome, signs of climate change can be read from increasing risk to climate related hazards. Globally observed changes may introduce certain deleterious environmental changes leading to enhanced vulnerability of people and their livelihoods (Ford and Goldhar, 2012) and risk of disasters (Chandel and Brar, 2010, 2011). This fact necessitates the importance of bringing global level information down to regional and local levels so that potential impacts of climatic changes can be envisaged and addressed at an appropriate geographical scale. Therefore, effort has been made in this study to examine annual and seasonal variability and trends in temperature conditions with an emphasis on direction and magnitude of change that has taken place in north-western India particularly in Punjab and Himachal Pradesh for over last 100 years. The analysis also derives its significance from the fact that temperature controls water availability, ecosystem response and human activities related to agriculture and horticulture which are the backbone of this area.

Study Area

The study area roughly forms a quadrilateral region located between 29° 30′ to 33° 12′ north latitudes and 73° 55′ to 79°04′ east longitudes. It spans over two north-western Indian states of Punjab and Himachal Pradesh (Fig. 1). These two states are administratively contiguous and connection between them is far deeper due to strong physiographic, climatic and hydrological links. The geography of this region is climatically pivotal and diverse. The mighty Himalayas shield the region from extreme cold winds from the north, while temperature conditions over Punjab Plains are vital for determining the arrival of the monsoons. The geographical position of this region attracts western disturbances during the winters that cause substantial precipitation. Moreover, the three major basins of River Sutlej, Beas and Ravi form a hydrological link between the two states. The behaviours of climatic conditions in the upper reaches greatly influence the lower regions and vice versa. These snow fed perennial rivers provide fresh water supply to most of the study area which is crucial for

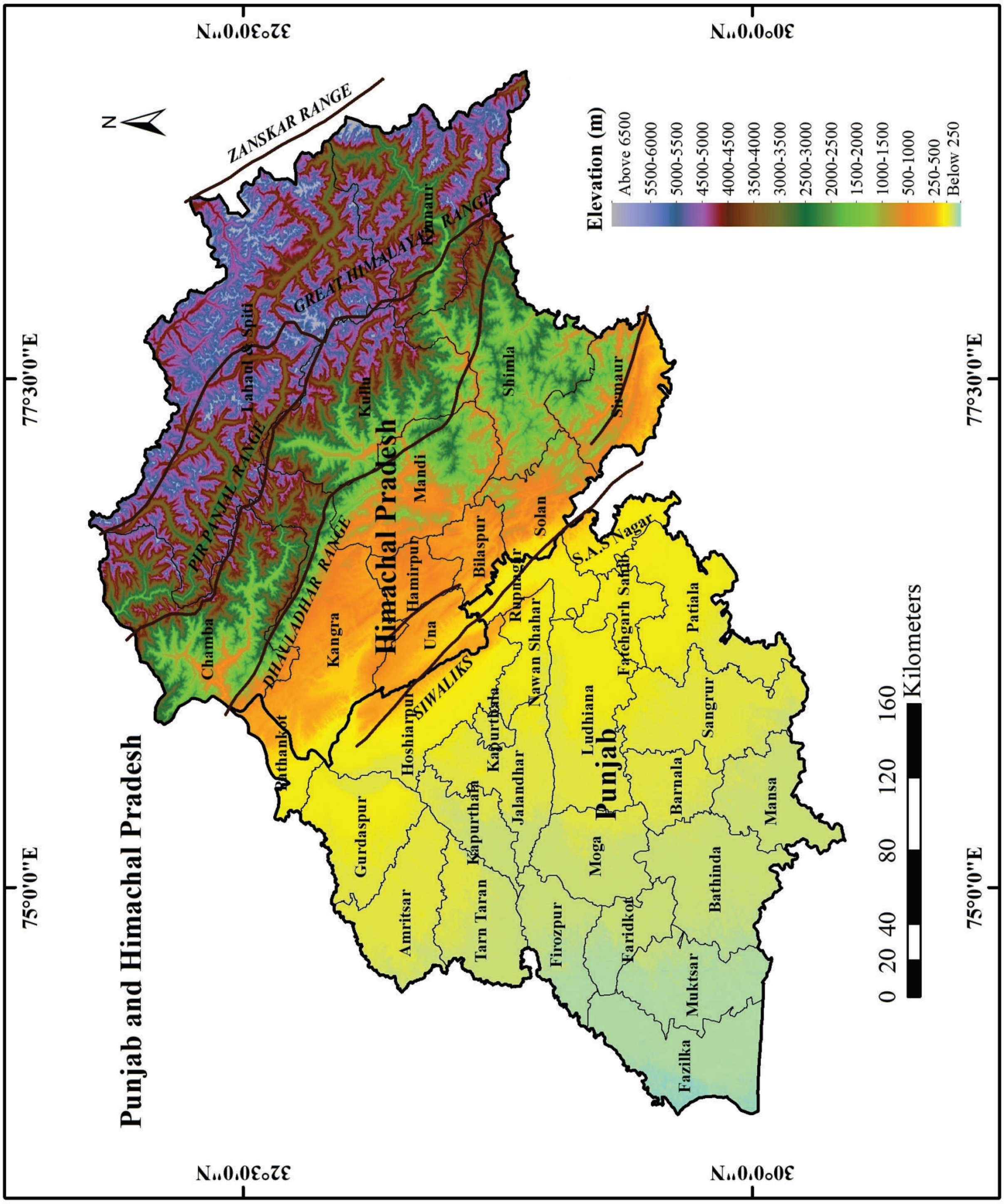

Punjab and Himachal Pradesh
32°30'0"N
30°0'0"N
75°0'0"E
77°30'0"E
N
ZANSKAR RANGE
GREAT HIMALAYAN RANGE
PIR PANJAL RANGE
DHAULADHAR RANGE
SIWALIKS
Himachal Pradesh
Punjab
Lahaul & Spiti
Kinnaur
Kullu
Chamba
Kangra
Mandi
Shimla
Sirmaur
Hamirpur
Una
Bilaspur
Solan
Pathankot
Gurdaspur
Amritsar
Tarn Taran
Kapurthala
Hoshiarpur
Jalandhar
Nawan Shahar
Rupnagar
S.A.S Nagar
Fatehgarh Sahib
Patiala
Ludhiana
Sangrur
Barnala
Mansa
Moga
Firozpur
Faridkot
Bathinda
Muktsar
Fazilka
Elevation (m)
Above 6500
5500-6000
5000-5500
4500-5000
4000-4500
3500-4000
3000-3500
2500-3000
2000-2500
1500-2000
1000-1500
500-1000
250-500
Below 250
0 20 40 80 120 160
Kilometers

Fig. 1

development as the key sectors of regional economy, viz. agriculture, horticulture, hydropower and tourism are dependent on favourable and stable climatic conditions. It is for these geographical and economic links, these two states have been taken as one unit to study the temperature regime so as to anticipate the implications of impending climatic change in this region.

Database and Methodology

This research paper examines temperature regime, based on long-term district-wise datasets for only 29 districts (18 for Punjab and 11 for Himachal Pradesh) out of the total 34 districts as long-term data was not available for each district. However, for meaningful interpretations the latest administrative boundaries were overlapped. The data pertain to 1901-2014 for Punjab but the data availability restricts the analysis for 1901-2002 in case of Himachal Pradesh. The datasets were compiled from the records available with National Data Centre, India Meteorological Department (IMD) Pune; India Water Portal and IMD Chandigarh to analyse the annual and seasonal behaviour of temperature change. IMD identifies 4 major meteorological seasons for the Indian subcontinent, viz. winter, pre-monsoon, monsoon, and post-monsoon. However, this classification does not represent a true picture of seasons for entire India due to country's huge spatial extent and diverse climatic regime. This is particularly true for the north-west India where study area is located. Therefore, a modified five season classification scheme (Brar, 2000) viz. winter (December-February), post-winter (March-April), summer (May-June), monsoon (July-September) and post-monsoon (October-November) has been used for the analysis of inter and intra annual temperature changes.

The variability in this study has been examined in terms of temperature characteristics such as mean, maximum mean and minimum mean temperature to identify the patterns and deviations from long-term average. Variability refers to magnitude of fluctuations from the mean that can be explained by range, standard deviation (SD) and coefficient of variability (CV). The range signifies absolute fluctuations; SD denotes the spread of probability distribution and CV is relative standard deviation usually shown in per cent to describe the levels of volatility. The higher CV indicates greater level of dispersion around the mean and hence higher potential for extreme temperature conditions. The other measures such as skewness and kurtosis have also been used to ascertain if temperature follows a normal distribution or not.

Trend estimation is based on two techniques, viz. Mann-Kendall Test and Sen's Slope Estimator (Mann, 1945; Kendall, 1975). The former is preferred over regression analysis as it is a non-parametric rank based procedure suitable for climatic data that may not follow a normal distribution. This technique is generally used for non-normally distributed data, datasets containing outliers and non-linear trends (Helsel and Hirsch, 1992) and is robust to the influences of extremes. Therefore, it is suitable for data with skewed variables such as climatic data wherein skewness tends present due to occurrence of extreme events. The second technique, i.e. Sen's slope estimator is also a non-parametric method widely used for determining the magnitude of trend and estimating the slope of trend in a hydro-meteorological time series (El Nesr et al., 2010; Tabari and Marofi, 2011; Tabari et al., 2011). This method is also insensitive to outliers or missing data and provides more realistic measure of trends compared to simple regression slopes (Hirsch et al., 1982). Due to their advantages, these two techniques have been preferred over simple regression techniques, namely:

Mann Kendall Technique

This technique is a non-parametric rank based procedure that explains significance in the levels of change. The test checks for null hypothesis of no trend versus alternative hypothesis of existence of increasing/decreasing trend. The test calculates values using the following formula:

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

where: n is the number of data points,
x_j and x_i are the data values in the times series I and j (j>i) and
$\text{sgn}(x_j - x_i) = +1$ if $(x_j - x_i) > 0$; 0 if $(x_j - x_i) = 0$ and -1 if $(x_j - x_i) < 0$.

In case, where the test sample size n>10, the standard normal test statistic (Zs) is calculated using following formula:

$Z_s = (S-1)/\sqrt{(\text{var}(S)}$ if $S > 0$
$Z_s = 0$ if $S = 0$
$Z_s = (S+1)/\sqrt{(\text{var}(S)}$ if $S < 0$

The positive Zs indicates increasing while negative values show decreasing trends. At 5% significance level, the null hypothesis is rejected if Z score i.e. $|Z_s| > 1.96$.

Sen's Slope Estimator

Sen's slope estimator is a more realistic method to determine the magnitude of trend and estimating the slope of trend. A positive value of slope indicates an upward or increasing trend whereas negative value indicates downward or decreasing trend in the time series. The actual values indicate steepness of the trend. Sen's slope estimator in the sample of N pairs of data is calculated as:

$$\mathbf{Q_i = (x_j - x_k)/(j-k) \text{ for } i = 1,2,3......N}$$

where, x_j and x_k are the data values at time j and k (j>k).

If there is only one datum in each time period, then N= n(n-1)/2, where n is the number of time periods. However, if there are multiple observations in one or more time periods, then N< n(n-1)/2. The N values of Qi are ranked from smallest to largest and median of slope or Sen's slope estimator is computed as:

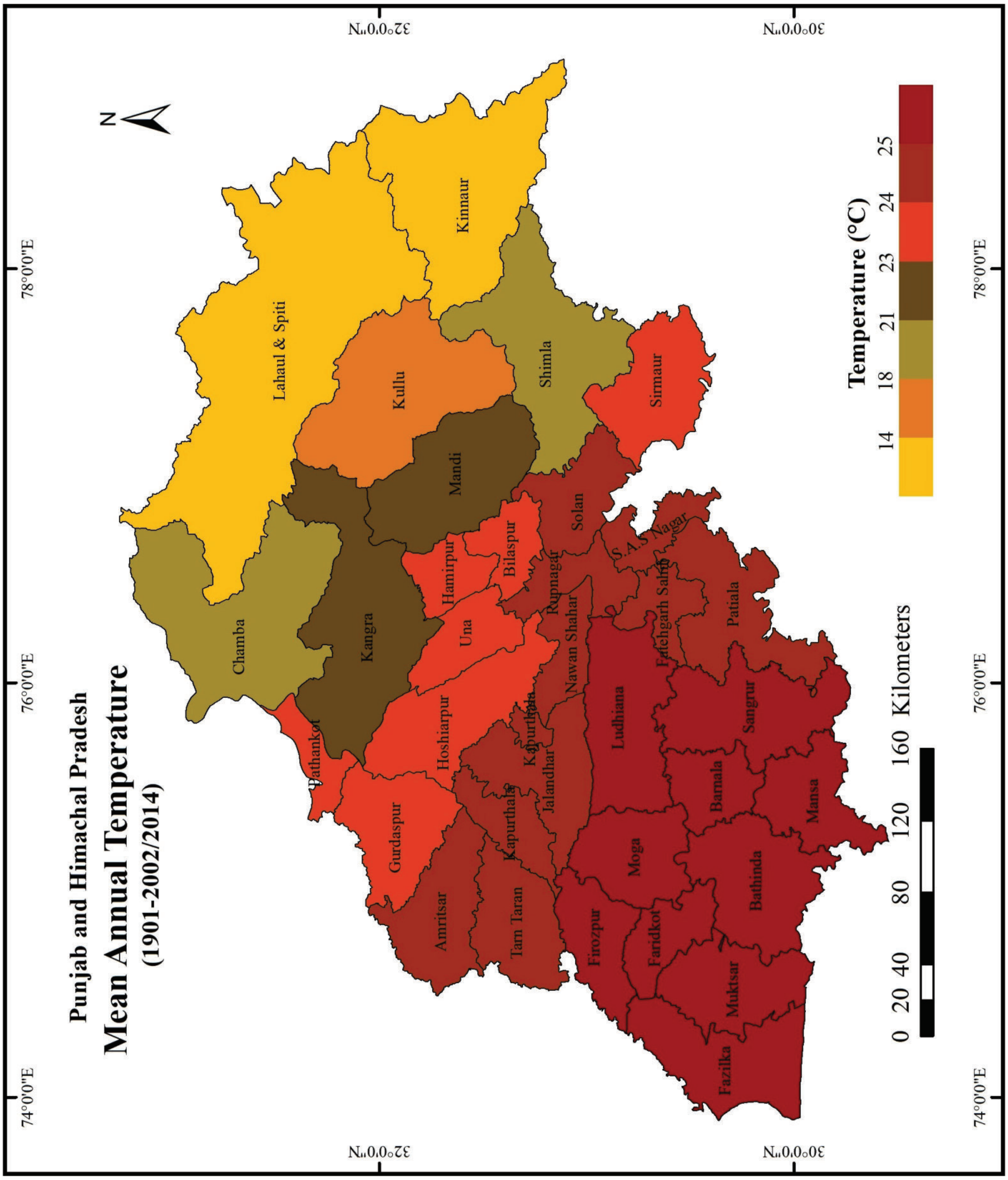
$Q_{med} = Q_{[(N+1)/2]}$ if N is odd;
$Q_{med} = (Q_{[N/2]} + Q_{[(N+2)/2]})/2$ if N is even

Results and Discussion

Patterns of Mean Annual Temperature

The annual temperature in the study area exhibit a clear zonation controlled by altitude. The long-term mean annual temperature ranges from 8.92°C to 25.39°C with a general direction of decrease from south-west to northeast (Fig. 2a). The districts located in Punjab Plains exhibit warm semi-arid to moist sub-humid climate with high mean annual temperature of more than 24°C and the maximum values of >25°C are recorded for south-western region of Punjab (Fig. 2a). The high mean temperature over Punjab Plains is attributed to its continental location, greater insolation, higher sunshine hours, radiational heating of air above and arid/semi-arid climate restricting cooling effect from evapotranspiration due to less vegetative cover and insignificant altitudinal variations.

However, mean annual temperature difference is more pronounced over Himachal Pradesh ranging between 23°C to 24°C in lower parts of the state. The temperature declines further in northward direction over temperate zone. The cold semi-arid/arid region, which include districts of Lahaul & Spiti and Kinnaur, experience mean temperature below 13°C, while the temperature dips to below 9°C in Lahaul and Spiti district (Table 1). Such relatively low temperatures over temperate and cold semi-arid zones of Himachal Pradesh are attributed to interior continental location and



Punjab and Himachal Pradesh
Mean Annual Temperature
(1901-2002/2014)
N
74°0'0"E
76°0'0"E
78°0'0"E
32°0'0"N
30°0'0"N
Lahaul & Spiti
Kinnaur
Kullu
Shimla
Sirmaur
Mandi
Chamba
Kangra
Solan
Bilaspur
Hamirpur
Una
S.A.S Nagar
Rupnagar
Fatehgarh Sahib
Patiala
Nawan Shahar
Hoshiarpur
Pathankot
Kapurthala
Jalandhar
Ludhiana
Sangrur
Gurdaspur
Amritsar
Tarn Taran
Barnala
Mansa
Moga
Bathinda
Firozpur
Faridkot
Muktsar
Fazilka
Temperature (°C)
14
18
21
23
24
25
0 20 40 80 120 160 Kilometers

Fig. 2a

Table 1
Punjab and Himachal Pradesh: Mean Annual Temperature Characteristics 1901-2002/2014

District	Mean Temperature (°C)	Maximum Mean Temperature (°C)	Minimum Mean Temperature (°C)	Temperature Range (°C)	Standard Deviation	Coefficient of Variation (Per cent)	Skewness	Kurtosis
Punjab (1901-2014)								
Firozpur	25.34	26.61	24.11	2.51	0.50	1.97	0.12	-0.23
Muktsar	25.23	26.63	23.18	3.46	0.70	2.77	-0.80	0.80
Faridkot	25.39	26.75	24.20	2.56	0.52	2.05	0.14	-0.19
Bathinda	25.27	26.66	24.03	2.63	0.53	2.10	0.24	-0.11
Mansa	25.15	26.69	23.18	3.51	0.69	2.74	-0.62	0.60
Moga	25.30	26.85	23.46	3.39	0.67	2.65	-0.43	0.36
Sangrur	25.05	26.50	23.74	2.77	0.55	2.20	0.21	0.00
Ludhiana	25.03	26.48	23.57	2.91	0.6	2.40	-0.04	-0.11
Jalandhar	24.65	25.89	23.31	2.59	0.54	2.19	-0.02	-0.11
Kapurthala	24.66	25.89	23.49	2.40	0.50	2.03	0.16	-0.27
Amritsar	24.62	25.91	23.18	2.73	0.54	2.19	-0.19	0.05
Patiala	24.79	26.06	23.49	2.57	0.50	2.02	0.22	-0.14
Fatehgarh Sahib	24.85	26.26	23.31	2.95	0.61	2.45	-0.13	-0.06
S.A.S Nagar	24.71	26.13	23.31	2.82	0.56	2.28	0.00	-0.06
Ropar	24.66	26.03	23.31	2.72	0.55	2.23	0.05	-0.10
Nawan Shahar	24.65	25.93	23.31	2.62	0.54	2.19	0.02	-0.12
Hoshiarpur	23.93	25.18	22.53	2.65	0.52	2.17	-0.07	0.02
Gurdaspur	23.63	24.67	22.58	2.09	0.43	1.82	0.27	-0.43
Himachal Pradesh (1901-2002)								
Una	23.97	25.22	22.81	2.41	0.46	1.90	0.34	-0.14
Sirmaur	24.00	25.49	22.78	2.71	0.47	1.96	0.36	0.27
Solan	24.32	25.69	23.07	2.62	0.48	1.97	0.32	0.01
Hamirpur	23.22	24.54	22.09	2.45	0.45	1.94	0.38	0.00
Mandi	22.07	23.49	20.92	2.57	0.46	2.08	0.40	0.16
Kangra	22.34	23.63	21.35	2.28	0.44	1.97	0.42	-0.03
Shimla	20.56	22.13	19.37	2.75	0.48	2.33	0.39	0.37
Chamba	19.32	20.63	18.47	2.16	0.44	2.28	0.43	0.00
Kullu	17.47	18.98	16.36	2.61	0.48	2.75	0.39	0.27
Kinnaur	12.69	14.37	11.59	2.79	0.50	3.94	0.39	0.55
Lahaul & Spiti	8.92	10.43	7.88	2.55	0.49	5.49	0.33	0.09

Source: Compiled by Authors

high altitude which controls the environmental lapse rate. The other associated factors are rarefied air and reduced insolation due to various altitudes of slope.

Variability of Mean Annual Temperature

Not much deviation in mean annual temperature has been recorded during 1901-2002/14 in the study area. The maximum values for annual mean temperature neither exceeded 27°C nor the minimum values dipped below 22°C in any part of Punjab Plains. However, over Himachal Pradesh, the mean temperature fluctuated between 23°C in the areas adjacent to Punjab plains to just below 9°C in the cold arid region. The intra-district mean annual temperature oscillated between 2°C to 4°C as manifested by range of temperature (Table 1). Despite a greater spatial variation, the intra-district range is less in Himachal Pradesh than Punjab suggesting that warmer climatic regions of Punjab especially the south and south-western parts are more likely to be affected by temperature fluxes as compared to Himachal Pradesh.

The low SD and CV values indicate low deviations from the mean. Within this low variation scenario, the maximum SD is observed for higher mean annual temperature areas of Punjab (Table 1) indicating greater year-to-year fluctuations compared to Himachal Pradesh. Although, the variability is also higher for Punjab, yet the cold semi-arid areas of Kinnaur and Lahaul & Spiti districts in the Greater Himalayan region show maximum variability (Fig. 2b). Following the thumb rule suggested by Bulmer (1979), the skewness values for study area fall in three categories. The majority of districts show a positive skewness (0-0.5) thereby indicating that inter-annual mean temperature remained below the long-term mean for a greater part of time with short periods of warm spell. A moderate skewness (-1 to -0.5) at Muktsar and Mansa districts indicates occurrence of short periods of cold spell. Similarly, kurtosis values explain the peakedness in distribution relative to normal distribution. Punjab exhibits platykurtic (negative) kurtosis that implies a flat distribution with very minor fluxes. About 12 districts of study area, most of which fall in Himachal Pradesh and south-western Punjab witnessed Leptokurtic (positive) kurtosis which suggests a higher degree of fluctuation in mean temperature (Table 1).

Trends in Mean Annual Temperature

Significant spatial variations are observed in the direction and magnitude of mean annual temperature over Punjab and Himachal Pradesh. Except for Patiala and Gurdaspur districts, the entire Punjab recorded decreasing trends with a statistically significant decrease (Zs> -1.96) in Mansa and Moga districts. The highest decrease is observed in Moga (0.57°C), Mansa (0.46°C) and Muktsar districts (0.46°C) during 1901-2002/14. However, the direction of change is quite opposite in Himachal Pradesh as entire hilly state exhibits an increase in mean annual temperature with statistically significant increase (Zs> 1.96) in 8 out of 11 districts (Table 2, Fig. 2c and 2d). The increase is greater over higher elevation areas with maximum increase (>0.60°C) in Lahaul & Spiti district followed by Kinnaur and Chamba districts (0.50°C-0.60°C). The remaining districts recorded an increase ranging between 0.30°C to 0.50°C.

The trend and magnitude of change is largely negative, i.e. mean annual temperature is declining with low levels of statistical significance in Punjab Plains over the dry semi-arid, dry sub-humid and moist sub-humid zones. However, a positive change is observed for Himachal Pradesh; the increase is statistically significant over temperate wet and moist and cold semi-arid/arid zones. Therefore, statistically significant increasing trend in majority of the districts indicate a definite warming in the hilly areas of Himachal Pradesh that might translate into critical ecological and environmental changes in the long run.

The mean annual temperature trends explain the direction and magnitude of change. However, by examining the maximum and minimum mean annual temperatures, it can be ascertained whether observed change is induced by alterations in day-time temperature or night-time temperature conditions. The analysis shows that maximum mean annual temperature representing day-time conditions and minimum mean annual temperature signifying night-time temperature have increased both for Punjab and Himachal Pradesh but the magnitude of change is greater and statistically significant in the latter (Table 2, Fig. 3a and 3b). The maximum and minimum

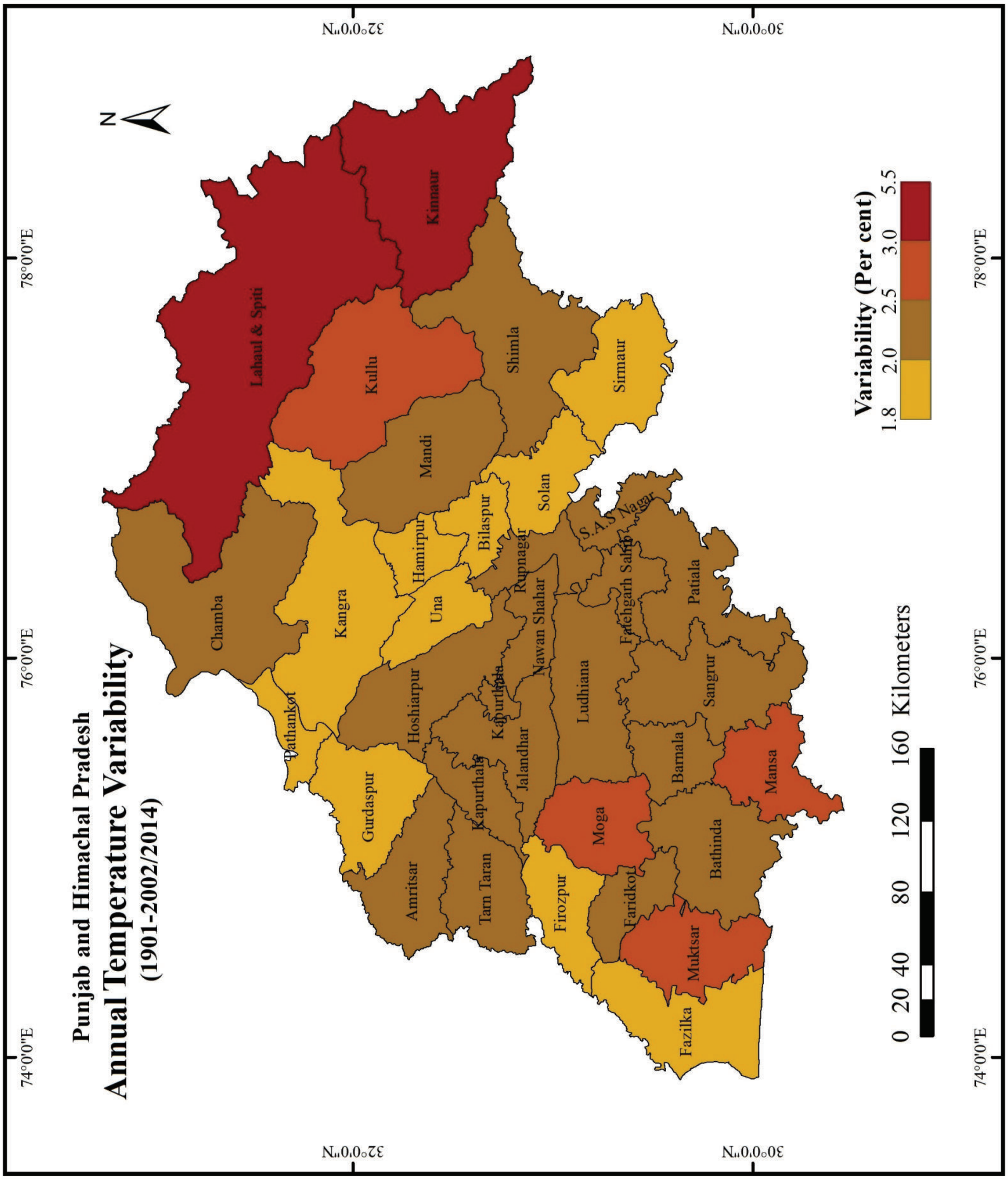
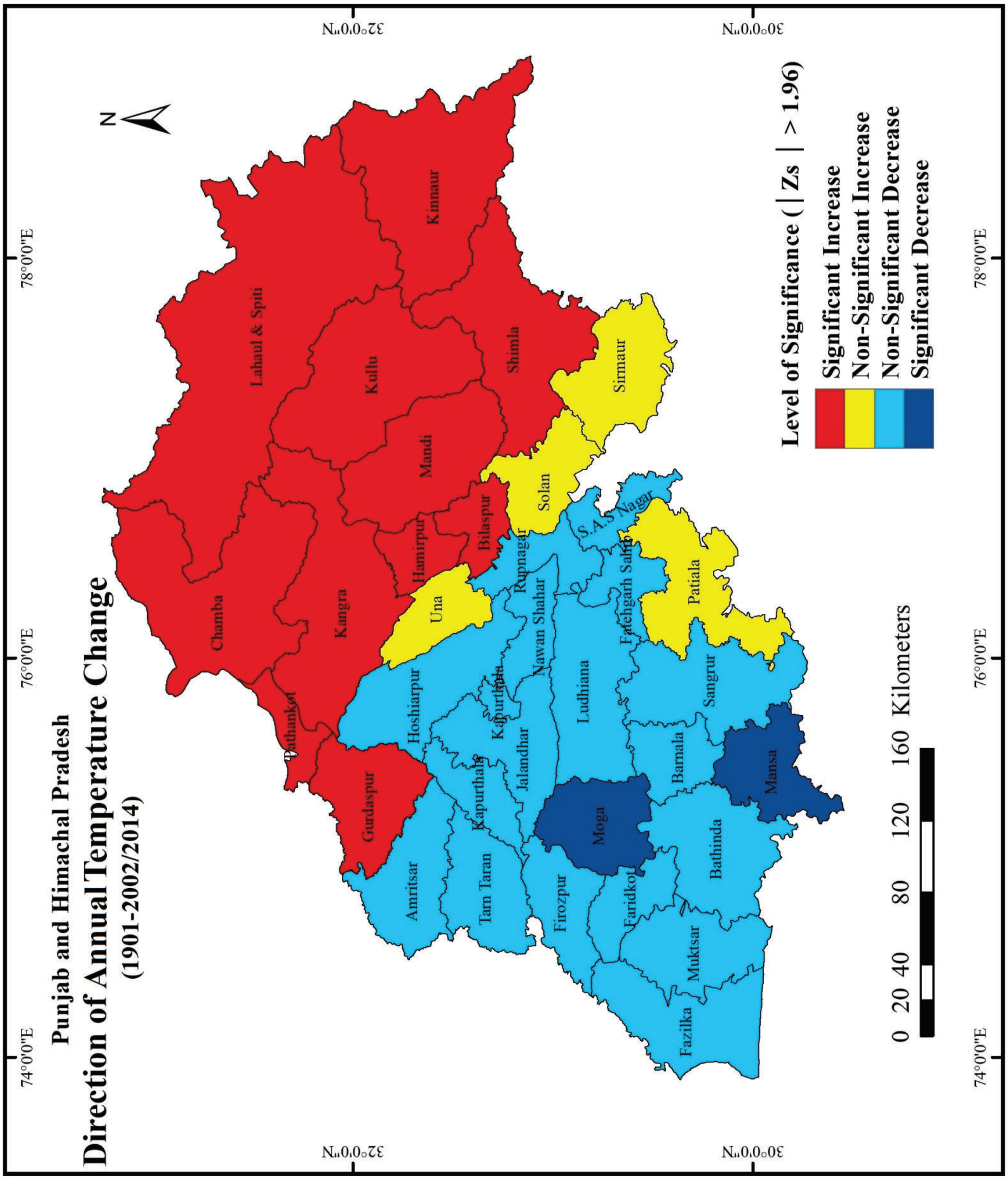

Punjab and Himachal Pradesh
Annual Temperature Variability
(1901-2002/2014)
N
Variability (Per cent)
1.8
2.0
2.5
3.0
5.5
0 20 40 80 120 160 Kilometers
74°0'0"E
76°0'0"E
78°0'0"E
32°0'0"N
30°0'0"N
Lahaul & Spiti
Kinnaur
Kullu
Shimla
Sirmaur
Chamba
Kangra
Mandi
Hamirpur
Bilaspur
Solan
Una
Rupnagar
S.A.S Nagar
Fatehgarh Sahib
Patiala
Pathankot
Hoshiarpur
Nawan Shahar
Ludhiana
Sangrur
Gurdaspur
Kapurthala
Jalandhar
Barnala
Mansa
Amritsar
Tarn Taran
Moga
Bathinda
Firozpur
Faridkot
Muktsar
Fazilka

Fig. 2b



Punjab and Himachal Pradesh
Direction of Annual Temperature Change
(1901-2002/2014)
N
Level of Significance (| Zs | > 1.96)
Significant Increase
Non-Significant Increase
Non-Significant Decrease
Significant Decrease
0 20 40 80 120 160 Kilometers
74°0'0"E
76°0'0"E
78°0'0"E
32°0'0"N
30°0'0"N
Lahaul & Spiti
Kinnaur
Kullu
Shimla
Chamba
Kangra
Mandi
Hamirpur
Bilaspur
Una
Solan
Sirmaur
Pathankot
Gurdaspur
Hoshiarpur
Amritsar
Tarn Taran
Kapurthala
Jalandhar
Nawan Shahar
Rupnagar
S.A.S Nagar
Fatehgarh Sahib
Patiala
Ludhiana
Sangrur
Barnala
Mansa
Moga
Firozpur
Faridkot
Bathinda
Muktsar
Fazilka

Fig. 2c

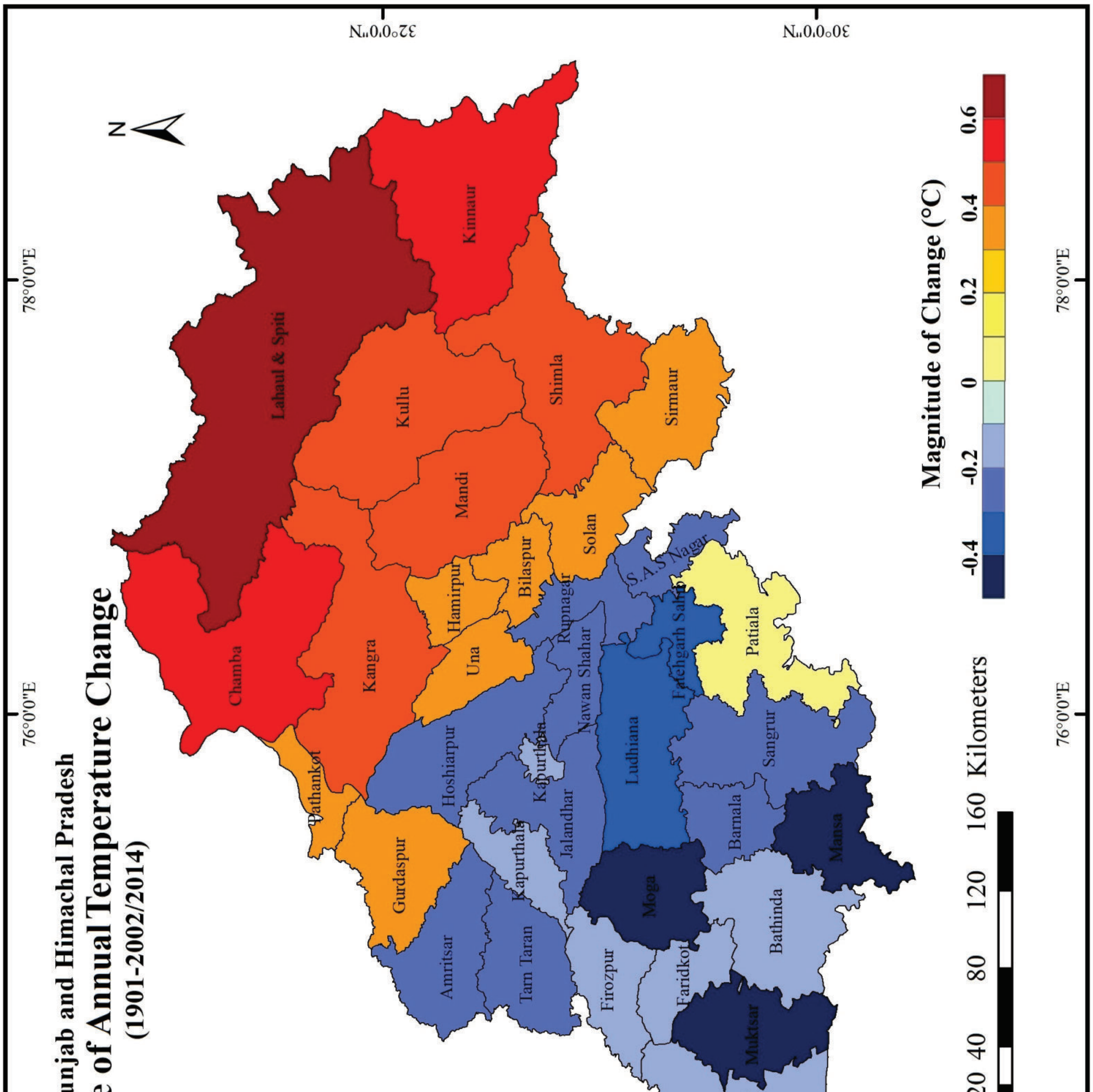

Punjab and Himachal Pradesh
Magnitude of Annual Temperature Change
(1901-2002/2014)
N
Lahaul & Spiti
Kinnaur
Chamba
Kangra
Kullu
Mandi
Shimla
Sirmaur
Solan
Bilaspur
Hamirpur
Una
Pathankot
Gurdaspur
Amritsar
Tarn Taran
Kapurthala
Jalandhar
Hoshiarpur
Nawan Shahar
Rupnagar
S.A.S Nagar
Fatehgarh Sahib
Patiala
Ludhiana
Sangrur
Barnala
Mansa
Moga
Firozpur
Faridkot
Bathinda
Muktsar
Fazilka
Magnitude of Change (°C)
-0.4
-0.2
0
0.2
0.4
0.6
0 20 40 80 120 160 Kilometers
74°0'0"E
76°0'0"E
78°0'0"E
32°0'0"N
30°0'0"N

Fig. 2d

Table 2
Punjab and Himachal Pradesh: Mean Annual Temperature Trends 1901-2002/2014

District	Mean Annual Temperature		Maximum Mean Annual Temperature		Minimum Mean Annual Temperature	
	Z_S	Q_{med} (°C)	Z_S	Q_{med} (°C)	Z_S	Q_{med} (°C)
Punjab (1901-2014)						
Firozpur	-0.446	-0.11	1.133	0.21	1.654	0.29
Muktsar	-1.815	-0.46	1.162	0.20	1.544	0.28
Faridkot	-0.940	-0.11	1.024	0.17	1.399	0.27
Bathinda	-0.774	-0.11	0.717	0.13	1.183	0.20
Mansa	-2.184	-0.46	0.867	0.15	1.214	0.23
Moga	-2.503	-0.57	0.168	0.03	0.746	0.14
Sangrur	-1.136	-0.23	0.636	0.12	1.018	0.19
Ludhiana	-1.724	-0.34	0.885	0.17	1.353	0.24
Jalandhar	-1.337	-0.23	1.041	0.18	1.865	0.31
Kapurthala	-0.945	-0.11	1.090	0.19	1.833	0.32
Amritsar	-1.376	-0.23	1.428	0.34	2.041	0.32
Patiala	0.069	0.01	1.122	0.20	1.532	0.27
Fatehgarh Sahib	-1.562	-0.34	1.162	0.19	1.538	0.29
S.A.S Nagar	-1.239	-0.23	1.301	0.22	1.738	0.34
Ropar	-1.151	-0.23	1.298	0.22	1.850	0.34
Nawan Shahar	-1.234	-0.23	1.272	0.22	1.752	0.32
Hoshiarpur	-1.264	-0.23	1.214	0.20	2.093	0.33
Gurdaspur	2.268	0.34	1.428	0.22	2.631	0.40
Himachal Pradesh (1901-2002)						
Una	1.856	0.31	1.492	0.26	2.163	0.36
Sirmaur	1.717	0.31	2.059	0.80	1.978	0.34
Solan	1.752	0.31	1.596	0.27	2.128	0.36
Hamirpur	2.163	0.31	1.946	0.73	2.544	0.40
Mandi	2.244	0.41	2.093	0.83	2.620	0.43
Kangra	2.394	0.41	1.957	0.73	2.909	0.45
Shimla	2.221	0.41	2.160	0.93	2.568	0.42
Chamba	3.024	0.51	2.247	0.90	3.562	0.58
Kullu	2.620	0.41	2.160	0.97	2.978	0.51
Kinnaur	2.964	0.51	2.727	0.46	3.071	0.57
Lahaul and Spiti	3.360	0.61	3.094	0.51	3.655	0.66

Source: Compiled by Authors

mean annual temperature over Punjab Plains has increased between 0°C to 0.34°C and 0.14°C to 0.40°C, respectively while the same were amplified by 0.26°C to 0.97°C and 0.34°C to 0.66°C in Himachal Pradesh. While increase in day-time temperature is insignificant for all districts of Punjab, the increase in the night-time temperature is found to be significant in Amritsar, Hoshiarpur and Gurdaspur districts only. The situation is precarious in Himachal Pradesh where 7 districts situated in the temperate and the cold semi-arid/arid climatic zones have recorded significant increase in day-time mean annual temperature. Also, the entire hill state display statistically significant increase in night temperature, however the

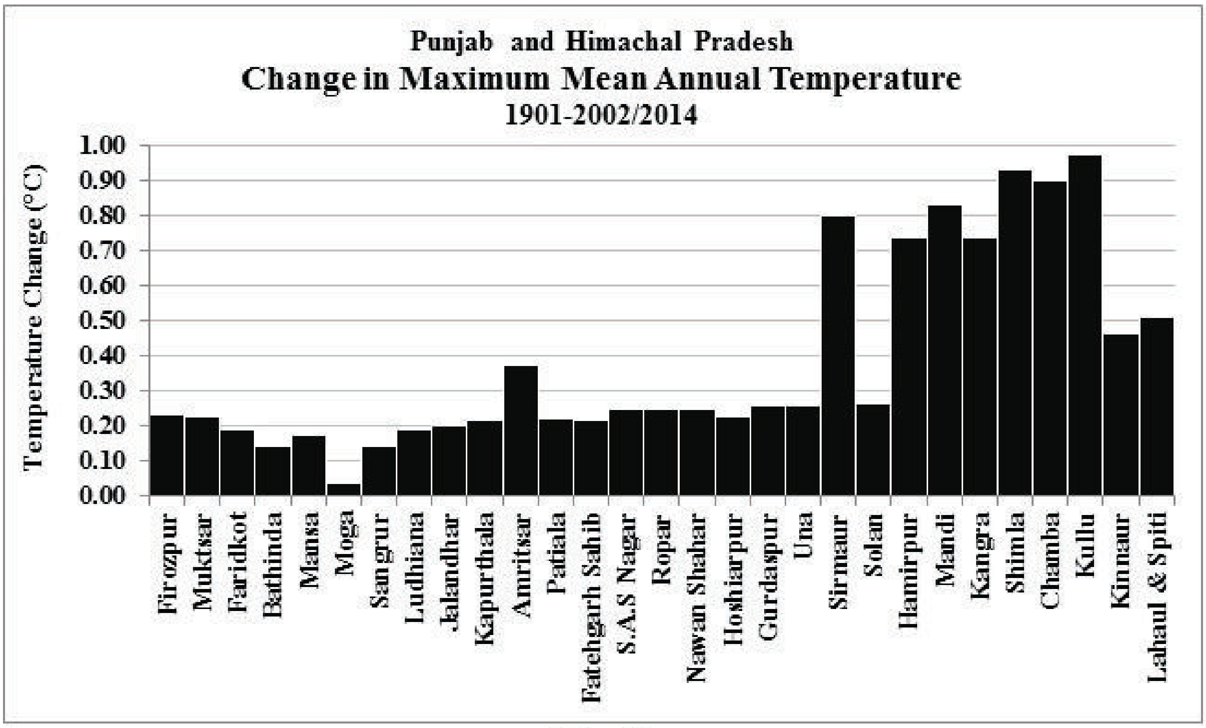

Punjab and Himachal Pradesh
Change in Maximum Mean Annual Temperature
1901-2002/2014
Temperature Change (°C)
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Firozpur
Muktsar
Faridkot
Bathinda
Mansa
Moga
Sangrur
Ludhiana
Jalandhar
Kapurthala
Amritsar
Patiala
Fatehgarh Sahib
S.A.S Nagar
Ropar
Nawan Shahar
Hoshiarpur
Gurdaspur
Una
Sirmaur
Solan
Hamirpur
Mandi
Kangra
Shimla
Chamba
Kullu
Kinnaur
Lahaul & Spiti

Fig. 3a

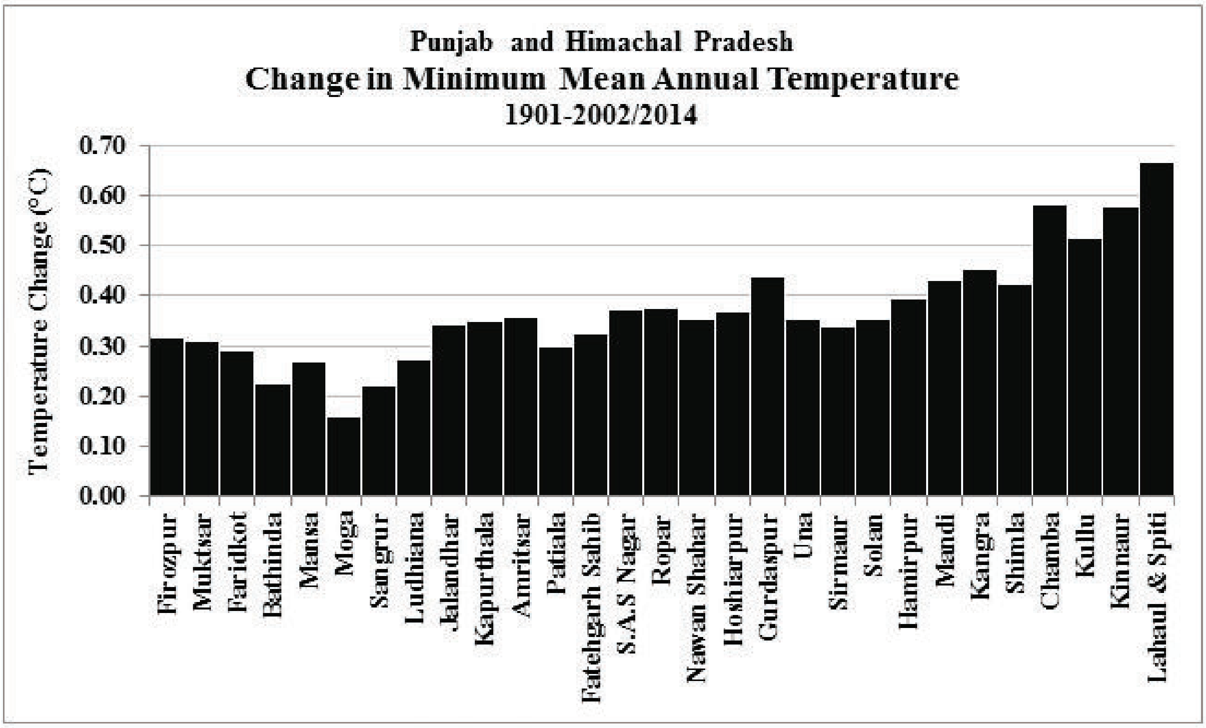

Punjab and Himachal Pradesh
Change in Minimum Mean Annual Temperature
1901-2002/2014
Temperature Change (°C)
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Firozpur
Muktsar
Faridkot
Bathinda
Mansa
Moga
Sangrur
Ludhiana
Jalandhar
Kapurthala
Amritsar
Patiala
Fatehgarh Sahib
S.A.S Nagar
Ropar
Nawan Shahar
Hoshiarpur
Gurdaspur
Una
Sirmaur
Solan
Hamirpur
Mandi
Kangra
Shimla
Chamba
Kullu
Kinnaur
Lahaul & Spiti

Fig. 3b

levels of significance are most critical in the Middle and the Great Himalayan regions.

The fact that mean annual temperature has gone down while maximum mean and minimum mean temperatures have increased in Punjab Plains predicting that there must be high level of contrast in seasonal direction of change in temperature conditions over Punjab in future. On the other hand, increasing mean, maximum mean and minimum mean temperatures in Himachal Pradesh clearly point towards warming in all the seasons.

Trends in Mean Seasonal Temperature

There are visible seasonal contrasts in the direction and magnitude of temperature change in the study area. An overall warming during winter season is evident as leaving aside Moga district, entire study area has recorded increase in temperature. The increase is statistically significant ($|ZS|> 1.96$) over all districts of Himachal Pradesh along with northern, south-eastern and south-western districts of Punjab. The magnitude of change is lowest (<0.4°C) for southern and central Punjab while northern districts of Gurdaspur and Pathankot exhibit maximum increase within Punjab Plains. The magnitude progressively amplifies towards the higher elevation regions of Himachal Pradesh; higher rates of warming occur over colder regions (Table 3, Fig. 4a and 4b). The lower and middle districts of the state have experienced warming up to 0.9°C whereas magnitude of temperature rise in the cool temperate and cold semi-arid regions has exceeded over 1°C during the last century.

The warming scenario is most critical during the post-winter season, as every district has recorded increasing trends with statistically significant change over entire Himachal Pradesh and majority of the districts of Punjab Plains. This magnitude of increase is higher than the winter season. The inter district variations are greater over Punjab (0.30°C to 1.60°C) but the rate of warming is more pronounced over Himachal Pradesh as all of the districts recorded an increase of over 1.0°C (Fig. 4c and 4d). As opposed to warming in winter and post-winter seasons, the trends in summer season show a different direction of change, particularly in Punjab where most of the districts show decrease in mean temperature. Statistically significant decrease has been recorded for Muktsar, Mansa, Moga and Fatehgarh Sahib districts. This decline in Punjab is as high as 1.15°C (Fig. 4e and 4f). However, in Himachal Pradesh except for Sirmour district, all the districts recorded increasing trends but these changes are not statistically significant with an increase of less than 0.3°C during the last century.

The monsoon season displays a complex situation as study area has experienced decrease in temperature. All the district of Punjab and majority of districts in Himachal Pradesh recorded statistically significant decline in temperature in monsoon season (Table 3, Fig. 4g and 4h). The magnitude of decline is much higher in Punjab than Himachal Pradesh with maximum decline of 1.0°C in south-western, southern and central Punjab. However, such decline in Himachal Pradesh varies from 0.2°C to 0.8°C with maximum decrease recorded for cold semi-arid and temperate regions of the state. The study highlights that such a significant decrease in temperature during monsoon season in the entire study area might have serious implications on precipitation patterns which in all probability are likely to get modified under this scenario of temperature change.

Temperature conditions during post-monsoon season display a contrasting trend for Punjab and Himachal Pradesh. Apart from Bathinda and Gurdaspur districts, the whole of Punjab recorded decreasing temperature

Table 3
Punjab and Himachal Pradesh: Mean Seasonal Temperature Trends 1901-2002/2014

District	Winter		Post-winter		Summer		Monsoon		Post-monsoon	
	Z_S	Q_{med} (°C)	Z_S	Q_{med} (°C)	Z_S	Q_{med} (°C)	Z_S	Q_{med} (°C)	Z_S	Q_{med} (°C)
Punjab (1901-2014)										
Firozpur	1.97	0.456	3.149	1.368	-1.14	-0.456	-5.49	-1.482	-0.48	-0.114
Muktsar	0.70	0.228	0.651	0.342	-2.49	-1.140	-5.72	-1.824	-2.18	-0.798
Faridkot	1.20	0.228	2.713	1.254	-1.25	-0.456	-5.45	-1.596	-0.97	-0.228
Bathinda	1.43	0.342	2.596	1.140	-1.05	-0.342	-4.69	-1.254	1.41	0.456
Mansa	0.50	0.114	0.544	0.220	-2.48	-1.026	-5.41	-1.710	-2.59	-0.798
Moga	-0.06	-0.017	1.085	0.456	-2.05	-0.912	-5.87	-1.938	-3.14	-0.912
Sangrur	1.57	0.342	2.611	1.140	-1.42	-0.456	-4.81	-1.368	-1.85	-0.570
Ludhiana	0.72	0.228	1.516	0.684	-1.54	-0.684	-5.43	-1.482	-2.52	-0.684
Jalandhar	1.59	0.342	2.322	1.026	-1.43	-0.570	-6.24	-1.482	-1.69	-0.456
Kapurthala	1.59	0.456	2.633	1.140	-0.84	-0.342	-5.99	-1.368	-1.05	-0.342
Amritsar	1.52	0.456	1.915	0.912	-1.78	-0.684	-6.13	-1.710	-1.59	-0.456
Patiala	2.08	0.570	2.586	1.140	-1.08	-0.342	-3.75	-0.798	-0.80	-0.228
Fatehgarh Sahib	1.11	0.342	1.322	0.570	-2.00	-0.798	-5.33	-1.254	-2.33	-0.684
S.A.S Nagar	0.66	0.158	1.457	0.644	-1.85	-0.623	-5.08	-1.058	-1.88	-0.474
Ropar	1.05	0.342	1.709	0.798	-1.74	-0.570	-5.37	-1.140	-1.68	-0.456
Nawan Shahar	1.30	0.342	2.062	0.912	-1.63	-0.570	-5.83	-1.254	-1.62	-0.342
Hoshiarpur	1.83	0.456	2.104	0.912	-1.76	-0.684	-6.26	-1.482	-1.10	-0.228
Gurdaspur	3.70	0.912	3.857	1.596	0.41	0.114	-5.24	-0.912	1.22	0.228
Himachal Pradesh (1901-2002)										
Una	3.36	0.918	2.799	1.224	0.56	0.204	-3.64	-0.714	0.86	0.204
Sirmaur	3.46	0.918	2.267	1.020	-0.12	-0.044	-3.02	-0.612	1.13	0.306
Solan	3.36	0.918	2.568	1.122	0.43	0.102	-3.24	-0.612	0.99	0.204
Hamirpur	3.36	0.918	2.781	1.224	0.51	0.102	-3.24	-0.612	1.13	0.306
Mandi	3.29	0.918	2.744	1.224	0.36	0.102	-2.61	-0.510	1.29	0.306
Kangra	3.35	0.918	2.886	1.224	0.60	0.204	-3.02	-0.510	1.08	0.306
Shimla	3.30	0.918	2.440	1.122	0.28	0.102	-2.32	-0.408	1.40	0.306
Chamba	3.63	1.122	3.076	1.224	0.63	0.204	-1.65	-0.306	1.41	0.306
Kullu	3.22	1.020	2.755	1.224	0.54	0.204	-1.79	-0.306	1.54	0.408
Kinnaur	3.42	1.122	2.359	1.122	0.41	0.102	-1.40	-0.306	2.11	0.612
Lahaul and Spiti	3.54	1.122	2.938	1.224	0.77	0.306	-0.99	-0.204	2.20	0.612

Source: Compiled by Authors

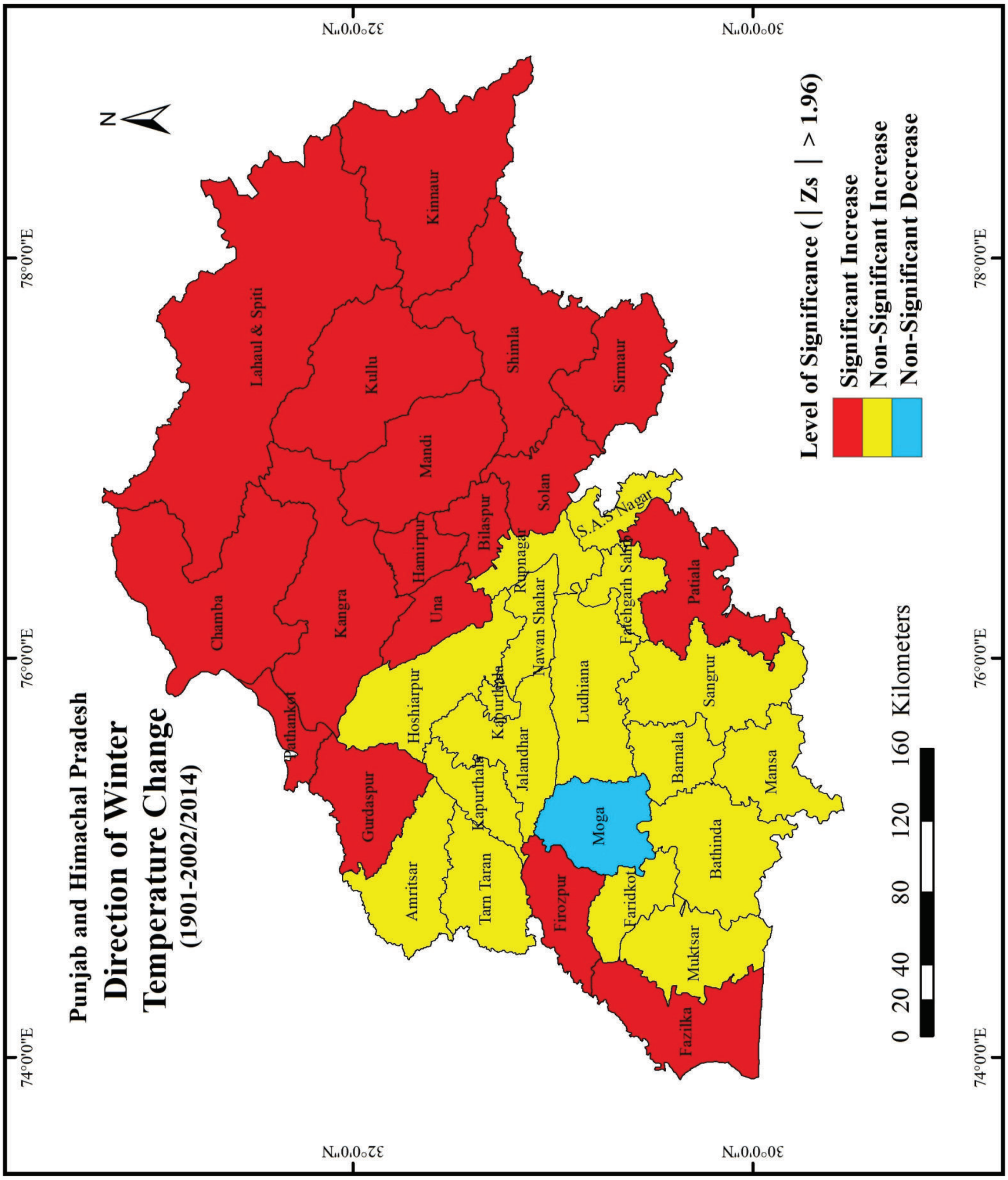

Punjab and Himachal Pradesh
Direction of Winter
Temperature Change
(1901-2002/2014)
N
Level of Significance (|Zs| > 1.96)
Significant Increase
Non-Significant Increase
Non-Significant Decrease
0 20 40 80 120 160 Kilometers
74°0'0"E
76°0'0"E
78°0'0"E
32°0'0"N
30°0'0"N
Lahaul & Spiti
Kinnaur
Kullu
Shimla
Sirmaur
Mandi
Solan
Chamba
Kangra
Hamirpur
Bilaspur
Una
Pathankot
Gurdaspur
Hoshiarpur
Rupnagar
S.A.S Nagar
Fatehgarh Sahib
Patiala
Nawan Shahar
Kapurthala
Jalandhar
Ludhiana
Sangrur
Barnala
Mansa
Amritsar
Tarn Taran
Moga
Firozpur
Faridkot
Bathinda
Muktsar
Fazilka

Fig. 4a

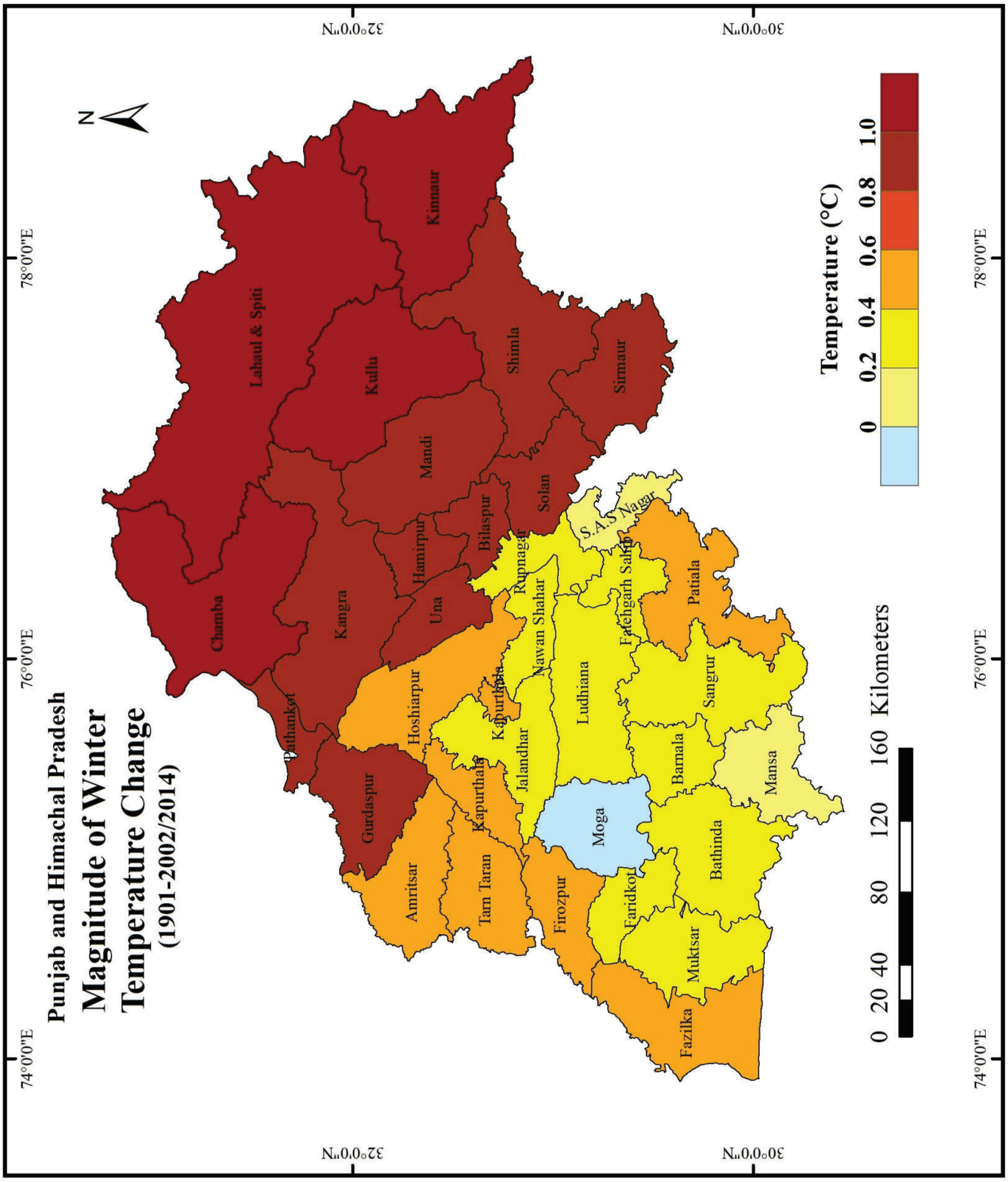

Punjab and Himachal Pradesh
Magnitude of Winter Temperature Change
(1901-2002/2014)
N
32°0'0"N
30°0'0"N
74°0'0"E
76°0'0"E
78°0'0"E
Lahaul & Spiti
Kinnaur
Kullu
Shimla
Sirmaur
Chamba
Kangra
Mandi
Hamirpur
Bilaspur
Solan
Una
Pathankot
Gurdaspur
Hoshiarpur
Rupnagar
S.A.S Nagar
Fatehgarh Sahib
Patiala
Nawan Shahar
Ludhiana
Kapurthala
Jalandhar
Amritsar
Tarn Taran
Moga
Barnala
Sangrur
Mansa
Bathinda
Faridkot
Firozpur
Muktsar
Fazilka
Temperature (°C)
0
0.2
0.4
0.6
0.8
1.0
0 20 40 80 120 160 Kilometers

Fig. 4b

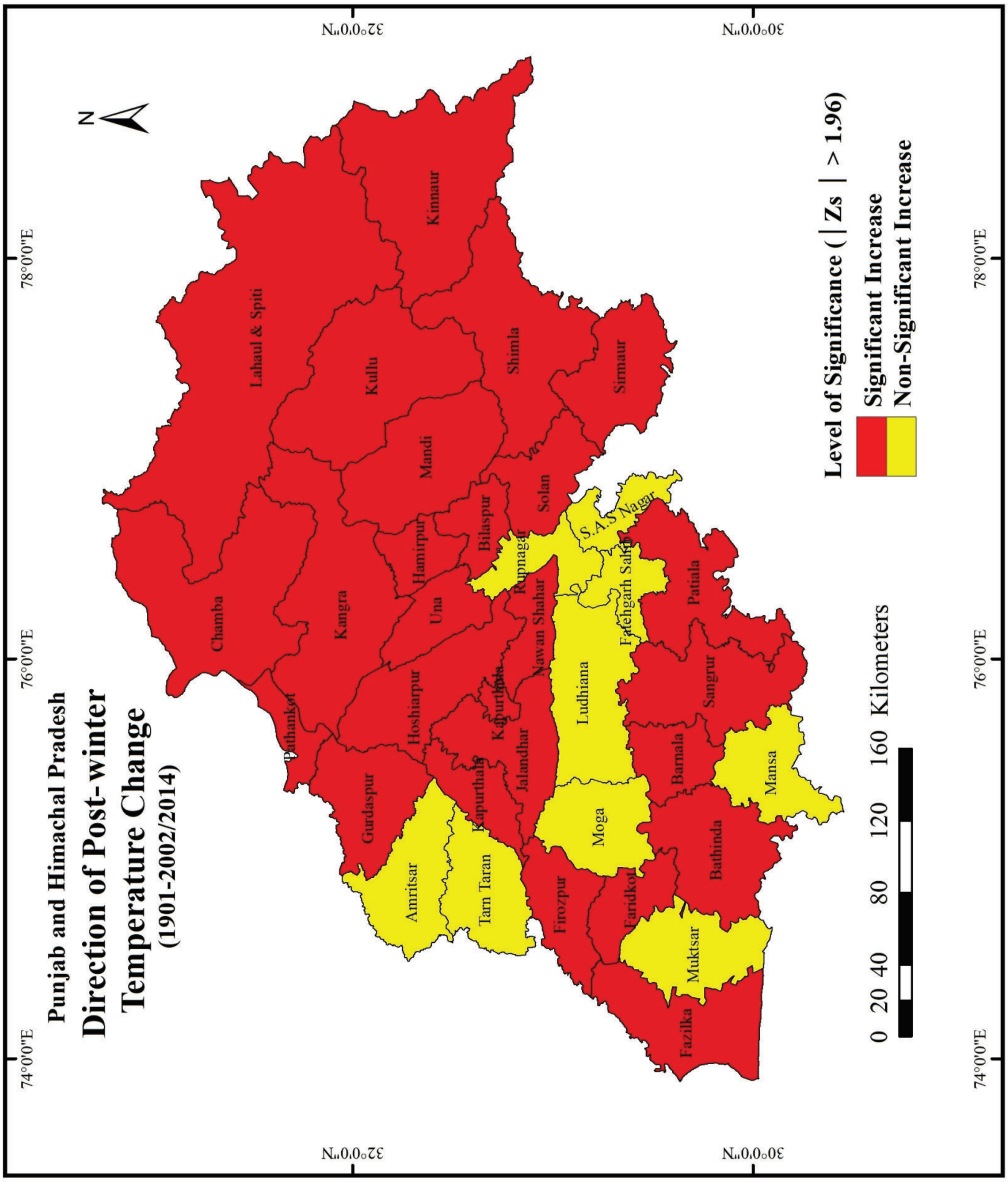
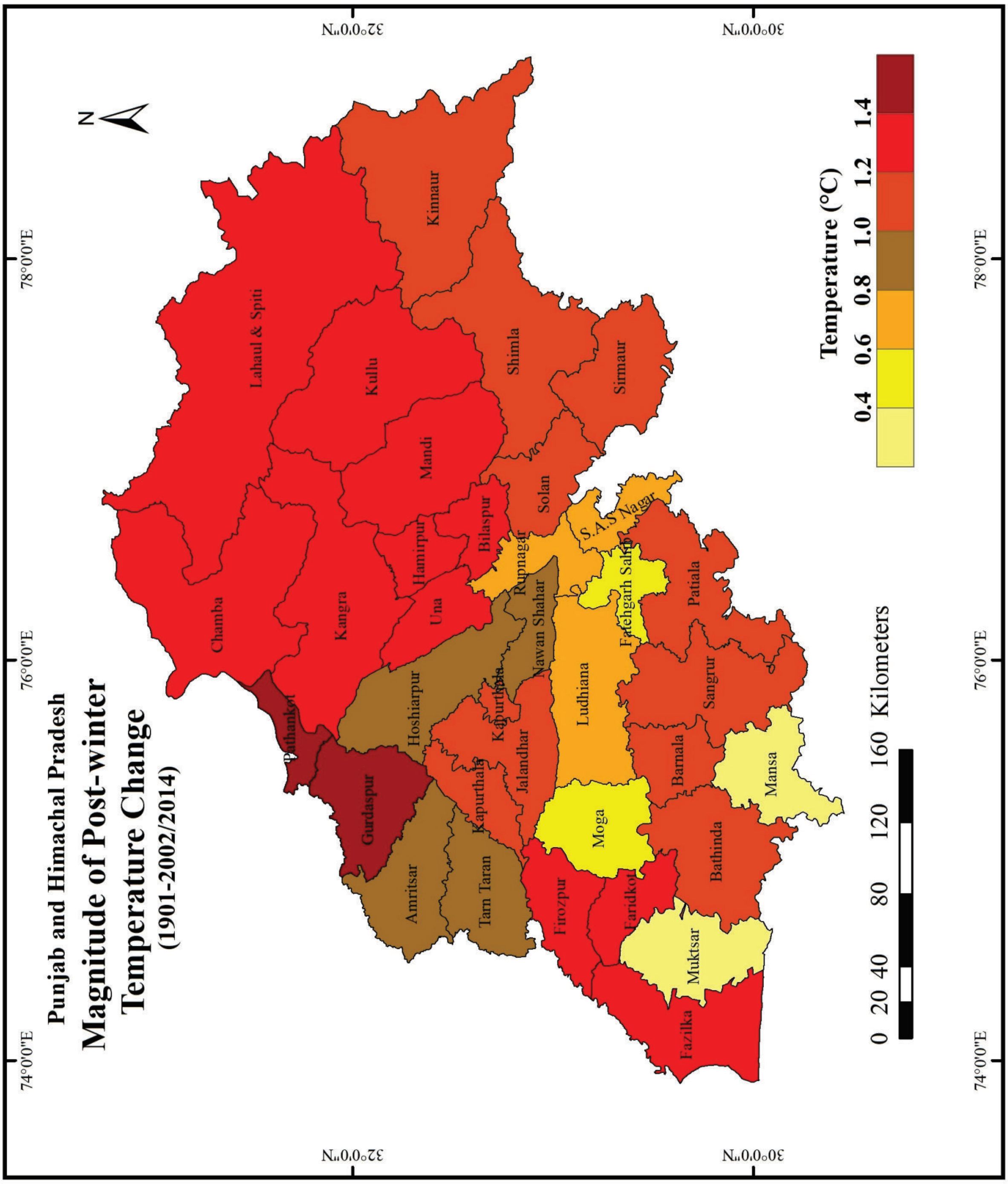

Punjab and Himachal Pradesh
Direction of Post-winter
Temperature Change
(1901-2002/2014)
N
Level of Significance (│Zs│ > 1.96)
Significant Increase
Non-Significant Increase
0 20 40 80 120 160 Kilometers
74°0'0"E
76°0'0"E
78°0'0"E
32°0'0"N
30°0'0"N
Lahaul & Spiti
Kinnaur
Kullu
Shimla
Sirmaur
Mandi
Chamba
Kangra
Hamirpur
Bilaspur
Solan
Una
S.A.S Nagar
Rupnagar
Fatehgarh Sahib
Patiala
Nawan Shahar
Hoshiarpur
Pathankot
Gurdaspur
Kapurthala
Jalandhar
Ludhiana
Sangrur
Barnala
Mansa
Moga
Amritsar
Tarn Taran
Firozpur
Faridkot
Bathinda
Muktsar
Fazilka

Fig. 4c



Punjab and Himachal Pradesh
Magnitude of Post-winter Temperature Change
(1901-2002/2014)
N
Temperature (°C)
0.4
0.6
0.8
1.0
1.2
1.4
0 20 40 80 120 160 Kilometers
74°0'0"E
76°0'0"E
78°0'0"E
32°0'0"N
30°0'0"N
Kinnaur
Lahaul & Spiti
Kullu
Shimla
Sirmaur
Mandi
Solan
Bilaspur
Hamirpur
Chamba
Kangra
Una
Pathankot
Gurdaspur
Hoshiarpur
Rupnagar
Nawan Shahar
S.A.S Nagar
Fatehgarh Sahib
Patiala
Ludhiana
Sangrur
Kapurthala
Jalandhar
Barnala
Mansa
Amritsar
Tarn Taran
Moga
Bathinda
Firozpur
Faridkot
Muktsar
Fazika

Fig. 4d

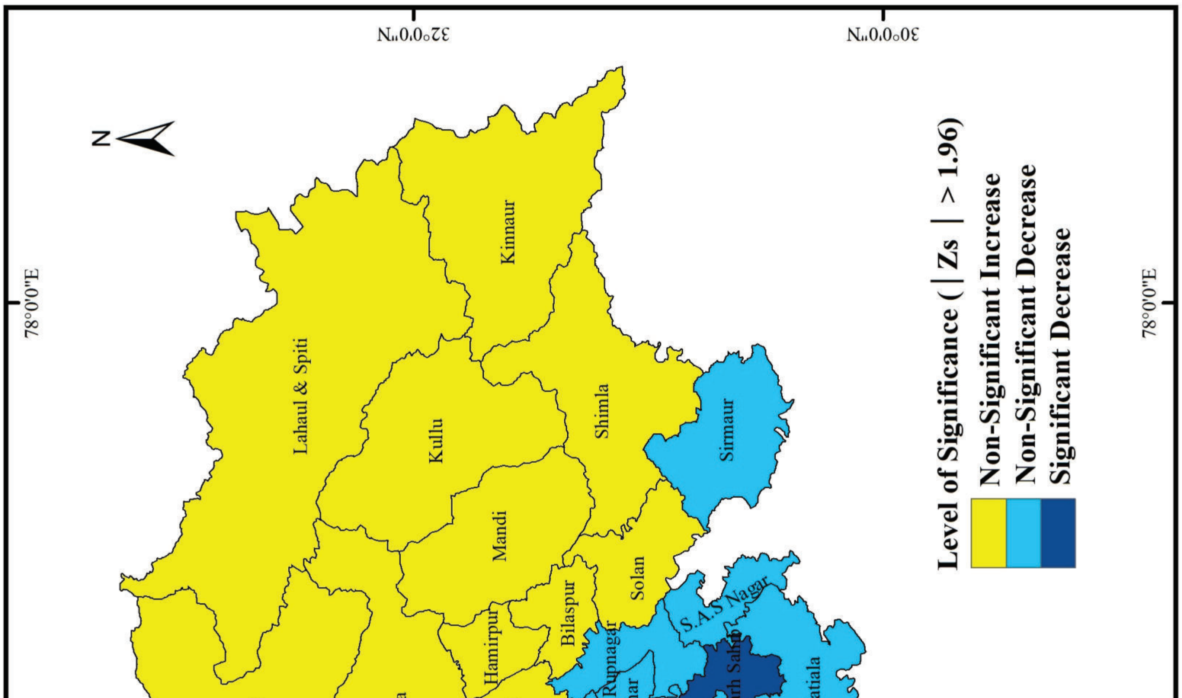

Punjab and Himachal Pradesh
Direction of Summer
Temperature Change
(1901-2002/2014)
N
Level of Significance (│Zs│ > 1.96)
Non-Significant Increase
Non-Significant Decrease
Significant Decrease
0 20 40 80 120 160 Kilometers
74°0'0"E
76°0'0"E
78°0'0"E
32°0'0"N
30°0'0"N
Lahaul & Spiti
Kinnaur
Kullu
Shimla
Chamba
Kangra
Mandi
Hamirpur
Bilaspur
Solan
Sirmaur
Una
Pathankot
Gurdaspur
Hoshiarpur
Amritsar
Tarn Taran
Kapurthala
Jalandhar
Nawan Shahar
Rupnagar
S.A.S Nagar
Fatehgarh Sahib
Patiala
Ludhiana
Sangrur
Barnala
Moga
Firozpur
Faridkot
Bathinda
Mansa
Muktsar
Fazilka

Fig. 4e

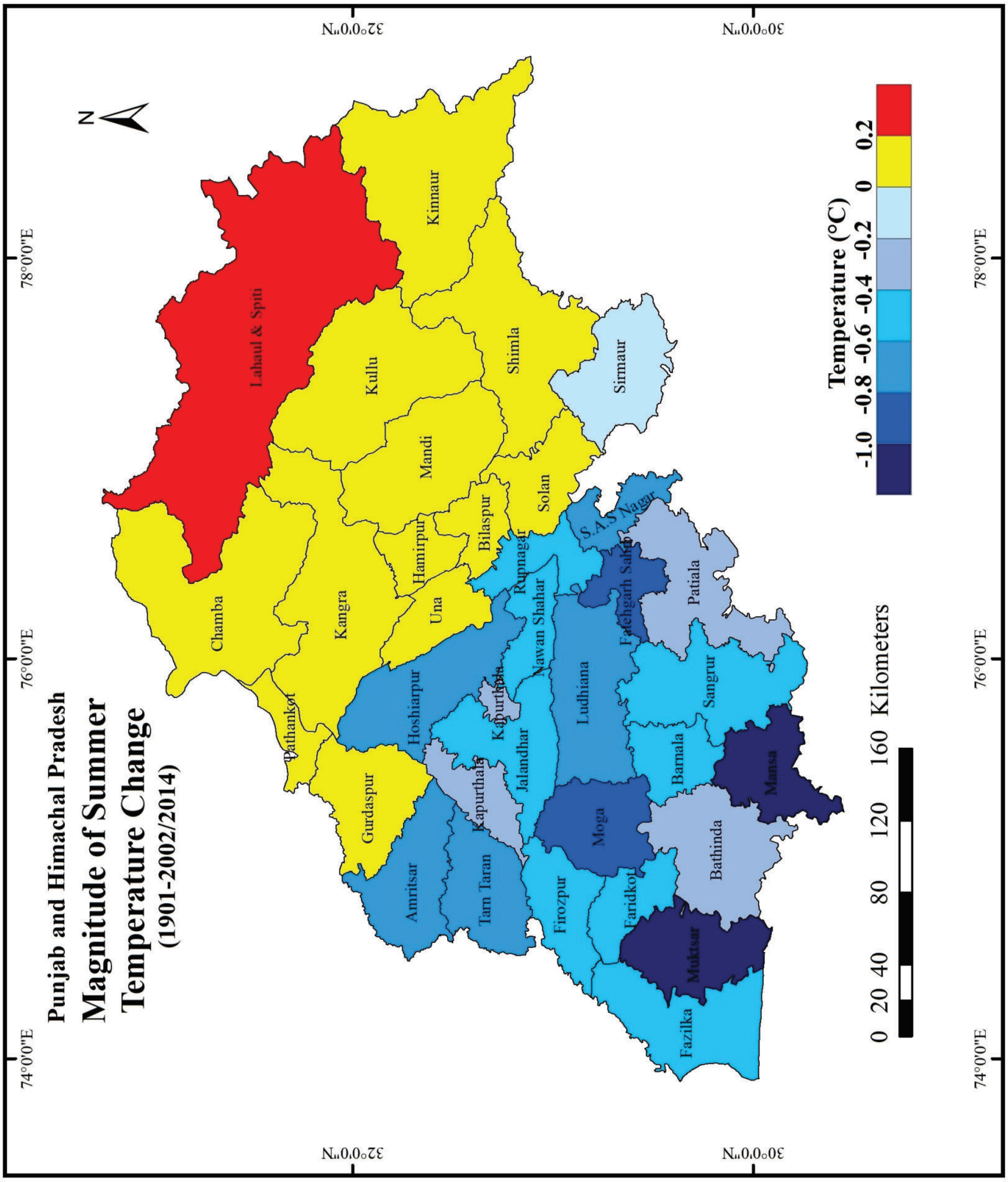

Punjab and Himachal Pradesh
Magnitude of Summer
Temperature Change
(1901-2002/2014)
N
Temperature (°C)
-1.0 -0.8 -0.6 -0.4 -0.2 0 0.2
0 20 40 80 120 160 Kilometers
74°0'0"E
76°0'0"E
78°0'0"E
32°0'0"N
30°0'0"N
Lahaul & Spiti
Kinnaur
Kullu
Shimla
Sirmaur
Mandi
Solan
Bilaspur
Hamirpur
Una
Chamba
Kangra
Pathankot
Gurdaspur
Hoshiarpur
Rupnagar
S.A.S Nagar
Fatehgarh Sahib
Patiala
Nawan Shahar
Kapurthala
Jalandhar
Ludhiana
Sangrur
Barnala
Mansa
Amritsar
Tarn Taran
Moga
Bathinda
Firozpur
Faridkot
Muktsar
Fazilka

Fig. 4f

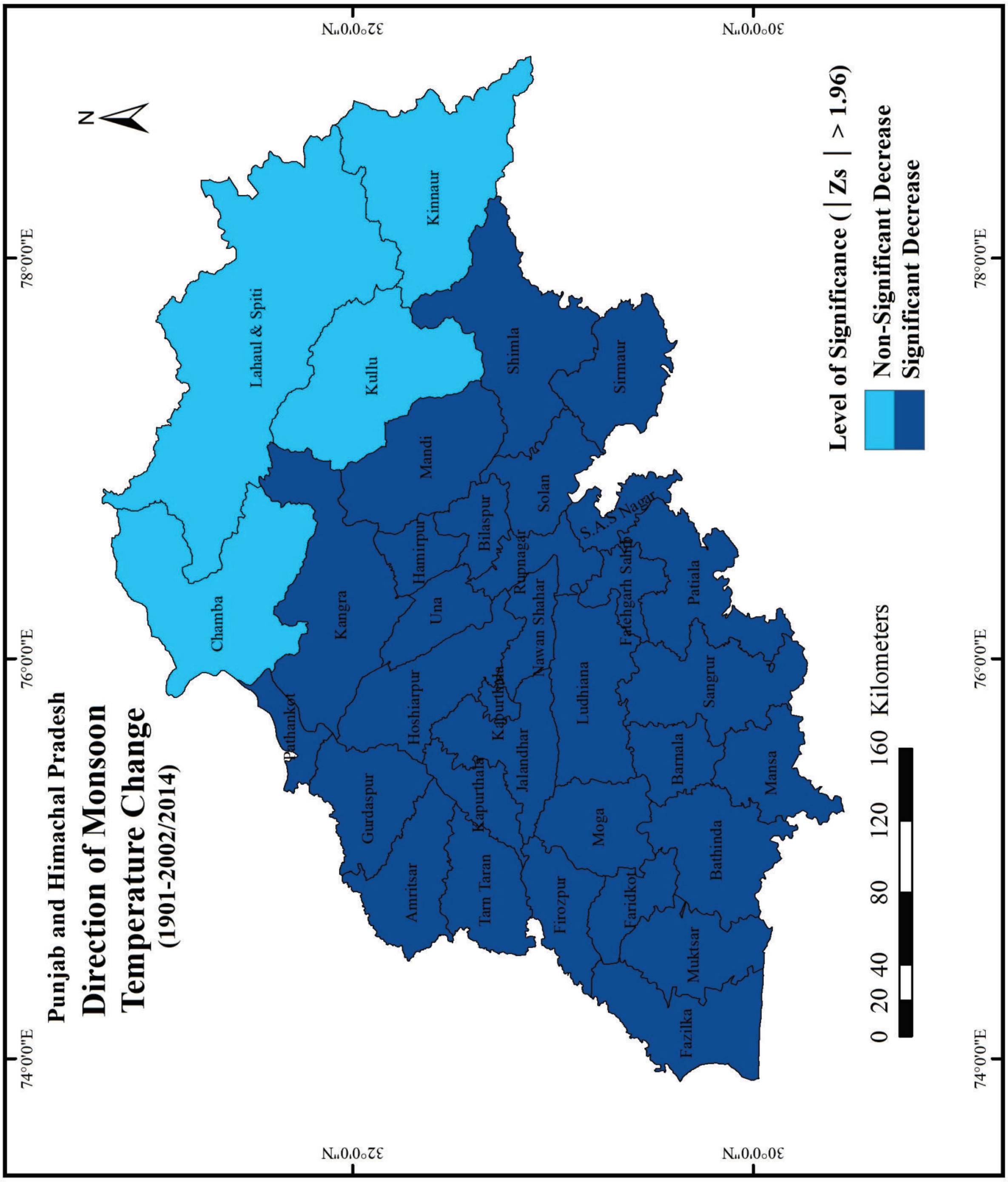

Punjab and Himachal Pradesh
Direction of Monsoon
Temperature Change
(1901-2002/2014)
N
Level of Significance (│Zs│ > 1.96)
Non-Significant Decrease
Significant Decrease
0 20 40 80 120 160 Kilometers
32°0'0"N
30°0'0"N
74°0'0"E
76°0'0"E
78°0'0"E
Lahaul & Spiti
Kinnaur
Kullu
Chamba
Kangra
Mandi
Shimla
Sirmaur
Solan
Bilaspur
Hamirpur
Una
S.A.S Nagar
Rupnagar
Fatehgarh Sahib
Patiala
Nawan Shahar
Hoshiarpur
Pathankot
Gurdaspur
Amritsar
Tarn Taran
Kapurthala
Jalandhar
Ludhiana
Sangrur
Barnala
Mansa
Moga
Bathinda
Firozpur
Faridkot
Muktsar
Fazilka

Fig. 4g

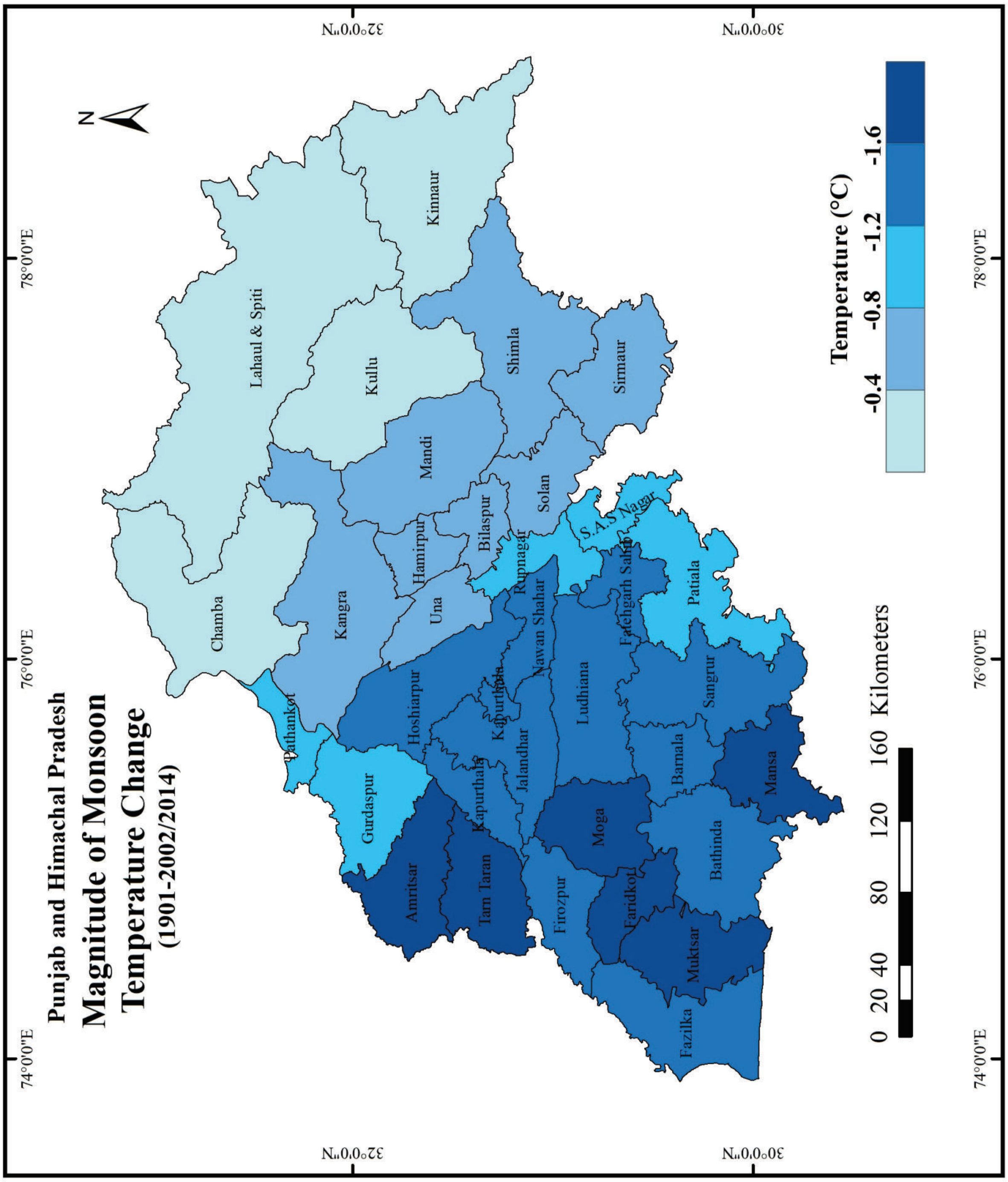

Punjab and Himachal Pradesh
Magnitude of Monsoon
Temperature Change
(1901-2002/2014)
N
Temperature (°C)
-0.4
-0.8
-1.2
-1.6
0 20 40 80 120 160 Kilometers
74°0'0"E
76°0'0"E
78°0'0"E
32°0'0"N
30°0'0"N
Lahaul & Spiti
Kinnaur
Kullu
Chamba
Kangra
Mandi
Shimla
Sirmaur
Solan
Hamirpur
Bilaspur
Una
Rupnagar
S.A.S Nagar
Patiala
Fatehgarh Sahib
Nawan Shahar
Hoshiarpur
Pathankot
Gurdaspur
Kapurthala
Jalandhar
Ludhiana
Sangrur
Barnala
Mansa
Amritsar
Tarn Taran
Moga
Bathinda
Firozpur
Faridkot
Muktsar
Fazilka

Fig. 4h

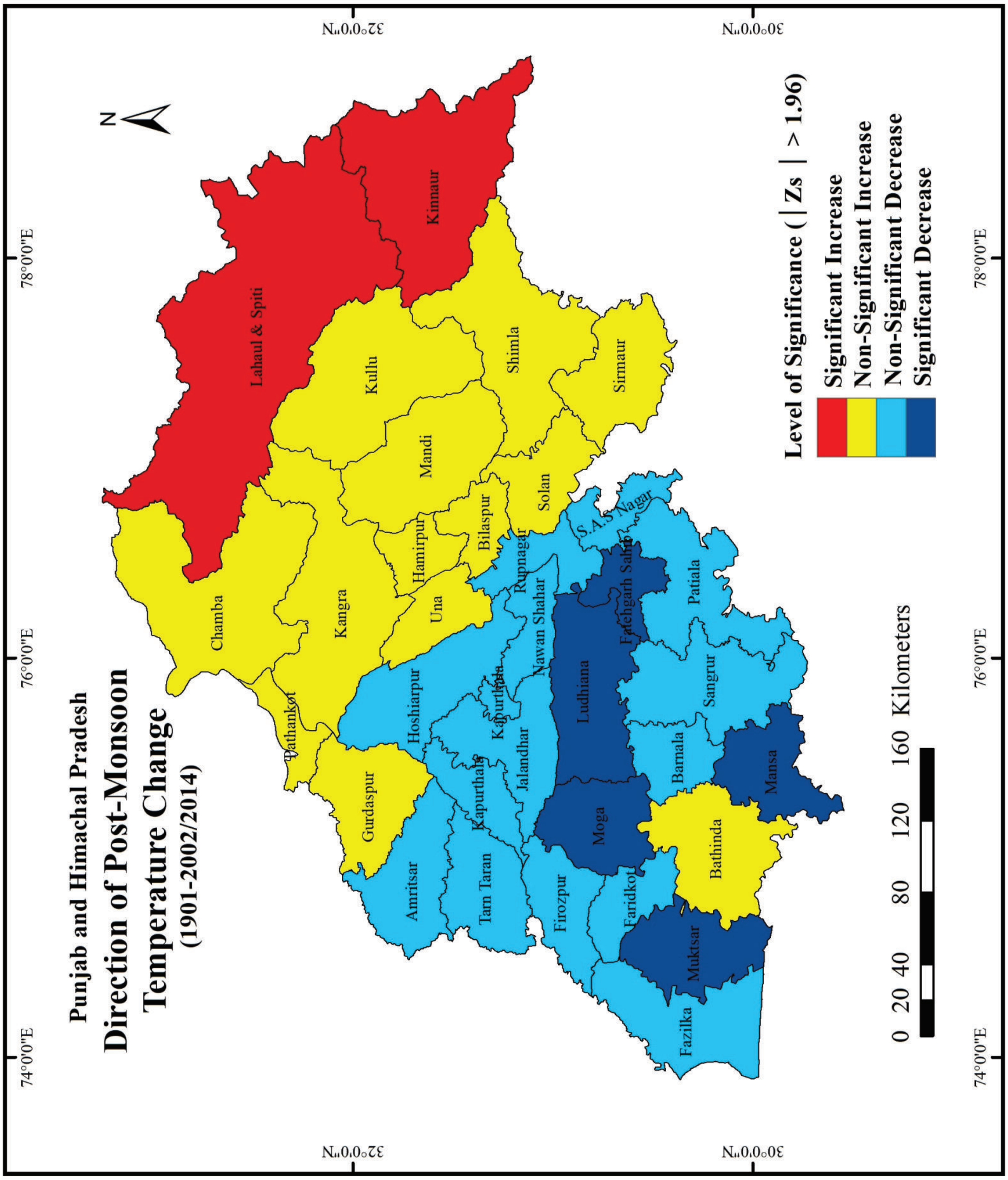

Punjab and Himachal Pradesh
Direction of Post-Monsoon Temperature Change
(1901-2002/2014)
Level of Significance (| Zs | > 1.96)
Significant Increase
Non-Significant Increase
Non-Significant Decrease
Significant Decrease
0 20 40 80 120 160 Kilometers
N
74°0'0"E
76°0'0"E
78°0'0"E
32°0'0"N
30°0'0"N
Lahaul & Spiti
Kinnaur
Kullu
Shimla
Sirmaur
Mandi
Solan
Bilaspur
Hamirpur
Chamba
Kangra
Una
Pathankot
Gurdaspur
Hoshiarpur
Amritsar
Tarn Taran
Kapurthala
Jalandhar
Nawan Shahar
Rupnagar
S.A.S Nagar
Fatehgarh Sahib
Patiala
Ludhiana
Sangrur
Barnala
Mansa
Moga
Firozpur
Faridkot
Bathinda
Muktsar
Fazilka

Fig. 4i

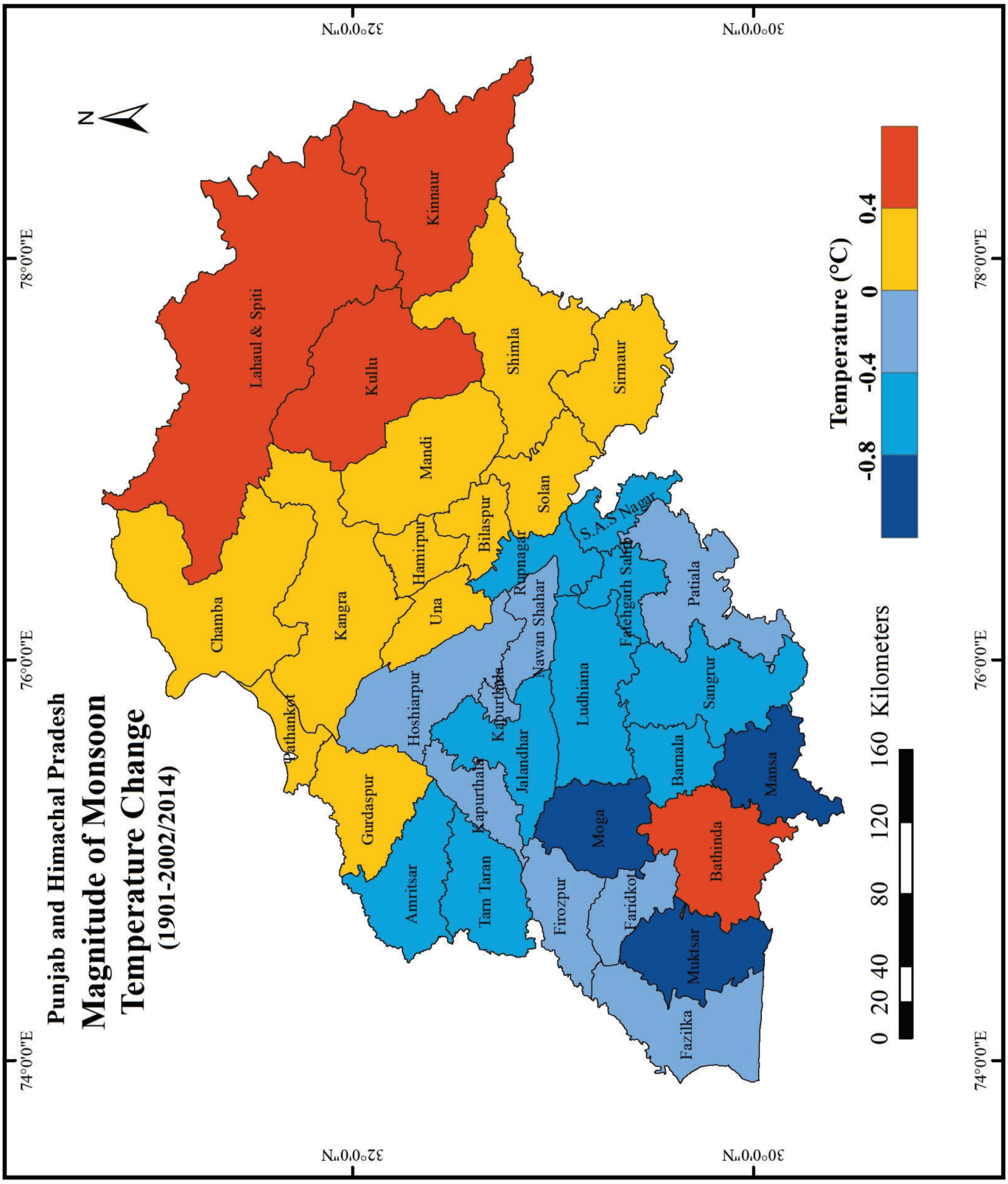

Punjab and Himachal Pradesh
Magnitude of Monsoon
Temperature Change
(1901-2002/2014)
N
Temperature (°C)
-0.8
-0.4
0
0.4
0 20 40 80 120 160 Kilometers
74°0'0"E
76°0'0"E
78°0'0"E
32°0'0"N
30°0'0"N
Lahaul & Spiti
Kinnaur
Kullu
Shimla
Sirmaur
Mandi
Solan
Bilaspur
Hamirpur
Chamba
Kangra
Una
Pathankot
Gurdaspur
Hoshiarpur
Rupnagar
S.A.S Nagar
Nawan Shahar
Fatehgarh Sahib
Patiala
Ludhiana
Sangrur
Kapurthala
Jalandhar
Barnala
Mansa
Amritsar
Tarn Taran
Moga
Bathinda
Firozpur
Faridkot
Muktsar
Fazilka

Fig. 4j

whereas entire Himachal Pradesh witnessed increasing trends (Table 3 and Fig. 4i and 4j). The temperature conditions in this season have dipped up to 0.8°C in Punjab with maximum decline in Moga, Mansa and Muktsar districts. On the other hand, an increase up to 0.6°C is recorded for Himachal Pradesh with maximum significant increase observed for Kinnaur and Lahaul & Spiti districts suggesting a comparatively higher degree of warming in the colder regions of the state.

On the whole, it is very clear that monsoon season depicts an unusual picture of declining temperature in the entire study area. Summer and post-monsoon seasons show decreasing trends in Punjab, while situation in these two seasons is just opposite for Himachal Pradesh. It is also very apparent that Punjab Plains have become relatively cooler, during summer, post-monsoon and monsoon seasons with highly significant dip in the latter while Himachal Pradesh depicted a minor fall in temperature during the monsoon season only. On the other hand, an overall warming has taken place during winter, post-winter, summer and post-monsoon seasons in Himachal Pradesh with a noticeable temperature rise in winter and post-winter seasons. The magnitude of warming is higher in colder regions of the state. Undoubtedly, during the last century, a definite warming of entire study area has taken place in winter and post-winter seasons; the magnitude of warming is particularly high in the high elevation areas of temperate and cold semi-arid/arid regions of Himachal Pradesh. Such a change in the high-altitude areas is most likely to have negative impacts on snowfall conditions and snowpack accumulation during winters and snow ablation in summer season.

Conclusions

Climatic fluctuations displayed significant changes during 20th century in Punjab and Himachal Pradesh. The analysis of annual and seasonal temperature changes reveals striking facts about the direction and magnitude of change over space and time. The south-west to north-east decreasing trends in temperature display a great influence of altitudinal zones. Punjab Plains exhibit higher mean temperatures but inter-district deviations in Himachal Pradesh are much more pronounced. The mean annual temperature over entire Punjab has declined whereas Himachal Pradesh has recorded significant increase indicating warming. Also, increase in both day-time and night-time mean temperature in both the states suggest enhancement in mean annual temperatures with higher magnitude in Himachal Pradesh.

The inter-seasonal change in temperature suggests a perilous picture. Mean temperatures are highly variable in winters and post winters; the mountainous areas of Himachal Pradesh exhibit greater variability in all seasons as compared to Punjab Plains. The cold semi-arid zone of Himachal Pradesh has shown most volatile temperature conditions. The warming trend during the past century has been most pronounced in Himachal Pradesh where the Greater Himalayan region has been warmed by 1°C. The magnitude of increase in post-winters is higher than winter season with statistically significant rise in the study area. Surprisingly, as opposed to general expectation, the temperature in summer season has gone down in Punjab but Himachal Pradesh exhibits increasing trend. The lowering of mean temperature during monsoon season is evident but magnitude of decrease is much higher in Punjab Plains. The post-monsoon season shows contrasting picture; the temperatures have declined in Punjab by up to 0.8°C, whereas an increase up to 0.6°C has been recorded in some parts of Himachal Pradesh.

It can be concluded with conviction that

Punjab Plains have become relatively cooler during summer, post-monsoon and monsoon seasons. A visible warming in Himachal Pradesh during winter, post-winter, summer and post-monsoon seasons has also taken place. The overall regional increase in temperature, particularly in winter and post-winter seasons, raises serious concerns about implications of climate change. The situation is critical as warming during winter and post-winter seasons is exceptionally higher in temperate and cold semi-arid/arid zones of Himachal Pradesh where cold conditions during the winter season are very critical for sustaining water resources and maintaining hydrological balance upon which rests the economic development of the study area.

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